TITLE

DETERMINATION OF MINIMUM POOL LEVEL FOR QUABBIN RESERVOIR ON THE BASIS OF WATER QUALITY CONSTRAINTS

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CHAPTER 1

INTRODUCTION

The design and operation of surface reservoirs are directly influenced by estimates of safe yield. The safe yield of a surface reservoir is the amount of water which can be supplied reliably to consumers over a specified period of time. Historically, the determination of safe yield has been based on hydrologic factors. While considerations of water quality have influenced the management and operation of water supply reservoirs, factors that influence the quality of impounded waters have been ignored in the determination of safe yield.

One of the key factors that influence water quality in a reservoir is depth of the water column. In cases where major reduction in depth of the water column can occur, it is important to consider if there may be a minimum to which reservoir depth can be lowered without incurring unacceptable impairment of water quality. This minimum is referred to as the "minimum pool level" for the reservoir.

The concept of the minimum pool includes a variety of normative as well as scientific considerations, including the determination of acceptable and non-acceptable degradations in water quality, the balance of public health and welfare and environmental aspects of water quality, the physical, chemical and biological dynamics of lacustrine ecosystems, and legal constraints imposed on reservoir operations by state and Federal law.

Just as the concept of a minimum pool is a highly integrative concept, so would its application in management practice increase the

potential for dealing with contemporary concerns about water supplies with an integrative management technique. Concerns that may be addressed through the application of the minimum pool concept include:

(1) Increasing public concern over the safety of public water supplies,

(2) Capacity of water supply managers to react to degradations in water quality in a timely and effective manner,

(3) Increasing finanacial costs for the design, construction, operation and maintenance of water treatment facilities,

(4) Concern for the realistic balance of the availability of potable water and community and business development, and

(5) Preservation and conservation of environmental resources.

The following sections focus on normative and scientific issues which can reasonably be expected to influence any attempt to determine a minimum pool level for a water supply reservoir. An example of an application of these consideratons to an actual determination of a minimum pool is then provided in the form of a case study of Quabbin Reservoir in central Massachusetts. Finally, the case study determination of minimum pool level is examined to identify limitations to the suggested approach for the determination of a minimum pool.

CHAPTER 2

SAFE YIELD AND MINIMUM POOL CONCEPTS

The safe yield of a water supply reservoir is the maximim daily withdrawal that can be taken over a period of years in which there is a severe or prolonged drought (Ingram *et al*., 1969; Fair *et al*., 1966; Gray, 1973). Essentially, the safe yield is therefore an amount of water (typically expressed as millions of gallons per day, or MGD) that serves as an index of the reliable delivery of water to consumers (Hellstrom, 1983).

The safe yield of a reservoir is not equivalent to the hydrologic yield of a reservoir. The finite volume of a reservoir results in overspill losses during periods when the reservoir is full. These overspill losses are part of the hydrologic yield of a reservoir, but are not part of the safe yield because they are not available for withdrawal to the consumer. Other such losses include losses through evaporation, seepage, and controlled releases that may be legally required for downstream augmentation.

There are different methods and approaches for computing safe yield. For example, safe yield may be calculated on the basis of historic hydrologic data which include an extremely low probability drought (e.g., a 100-year drought, or one which is likely to occur only once in a hundred years), or on the basis of limited historic hydrologic data which do not include such a low probability drought. The former approach has been referred to as the "hydrologic safe yield"; the latter, the "planning safe yield" (Hellstrom, 1983).

Different determinations of both hydrologic and planning safe yields may be made, depending on the criterion of withdrawal reliability selected. For example, it may be desirable to ensure a specified withdrawal over a period of time with essentially a 100% reliability; in another case, it may be adequate to allow the reservoir to fail to meet that same withdrawal capability 3 months in a 5-year period (i.e., a 95% reliability). Reliabilities of substantially less than 100% are highly practicable in those instances in which there are alternative sources of water which can be used in periods of failure of the reservoir or in which there are other practicable measures for reducing demand on the water supply by consumers. Determinations of safe yield are currently largely based on consideration of historic hydrologic data. Limitations in the historic hydrologic data base, as well as the possibility that future droughts may be significantly more severe than previously recorded droughts, are important constraints in determining any withdrawal criterion (Burnham _et al_., 1981).

Reservoir Storage Levels

The vertical structure of reservoirs influences its reliability with respect to safe yield. This structure has been described in terms of a series of storage levels (Burnham _et al_., 1981):

- _Inactive Level_: extending from the lowest point of the reservoir up to the lowest outlet; this storage cannot be tapped for withdrawal; use of this storage is limited to recreation, sediment trapping and reservoir fisheries

- Water Supply Level: extending from the top of the inactive level to the highest outlet (excluding the uncontrolled spillway crest); this storage can be tapped for withdrawal for various purposes, including potable water supply, irrigation, hydropower, etc.; different depths within this storage may be tapped on a seasonal basis
- Flood Control Level: extending from the top of the water supply level to the uncontrolled spillway crest; this storage is used to store flood waters and may, on a seasonal basis, extend down into the water supply storage
- Surcharge Level: extending from the uncontrolled spillway crest to the maximum pool level of the reservoir; this storage is a transient storage which allows for a reduction in the size of the spillway

For purposes of this discussion, I will consider that the safe yield of a reservoir typically refers to the maximum daily withdrawal that can be "safely" taken (i.e., without hydrologic failure) from the water supply and flood control storage (i.e., from the lowest outlet up to the uncontrolled spillway crest). As noted above, in the case of a specific reservoir, this may not be strictly correct due to controlled releases for the purpose of downstream augmentation, seepage and other losses that cannot be tapped by the consumer.

Reservoir Operational Rules

For any given hydrologic data base and criterion of withdrawal reliability, the safe yield of a water supply reservoir is a function not only of its physical storage capacity (i.e., water supply plus flood control storage) but also of those operational rules that govern flows into and out of the reservoir (Hellstrom, 1983). Historically, operational rules which influence safe yield determinations have been predicated on concerns for water quantity as opposed to concerns for water quality. Examples of operational rules based largely on concerns for water quantity and which directly influence the determination of safe yield include the following:

(1) Minimum discharge requirements for downstream augmentation; these requirements are often legally mandated at state or Federal levels to ensure that downstream needs for navigation, domestic supply, industrial use, waste dilution, etc. are met.

(2) Interbasin transfers of riverine waters into reservoirs; these requirements are also legally mandated and are typically designed to ensure the continuance of historic riparian uses downstream from the point of transfer of riverine waters into the reservoir.

(3) Maintenance of reservoir storage to minimize evaporational losses; these are typically not legal requirements but reflect tactical operational decisions by water authorities concerned with water conservation in periods of drought.

(4) Watershed management alternatives to enhance runoff into reservoirs; these requirements are typically incorporated in state or

local long-term vegetation management plans for specific watersheds which focus on minimizing water losses through evapotranspiration.

(5) Interbasin transfers of reservoir waters to other reservoirs in multi-reservoir systems; these requirements vary greatly, depending upon the system considered; they involve a complex series of considerations of the overall system and its component parts, including the timing and amounts of transfer, different uses of the various reservoirs, and the occurrence of major meteorological and other events such as hurricanes, droughts, structural failures, etc.

Operational rules for a reservoir may be based on considerations of water quality as well as on considerations of water quantity. However, the use of such operational rules have typically been of short-term duration (i.e., with respect to the hydrologic data base) and have focused on limiting the amount, period and/or depth of reservoir withdrawal to reduce excessive color or turbidity in withdrawn waters. Generally, they have not been used as key factors in the determination of safe yield.

With increasing public concern over hazardous and potentially toxic chemicals in the environment there has been an increasing tendency to factor water quality concerns into the historic determination of reservoir safe yield. For purposes of this discussion, "minimum pool" will be used to denote the inclusion of water quality concerns in the safe yield determination.

Minimum Pool Concept

The concept of the minimum pool was originally formulated in the Massachusetts Metropolitan District Commission Water Supply Study and Environmental Impact Statement-2020 and was specifically applied to Quabbin Reservoir, a 412 billion gallon domestic water supply reservoir in central Massachusetts (WFA, 1983). In this original formulation, the minimum pool level for Quabbin Reservoir is defined as the lowest elevation to which the reservoir may be lowered at which there is reasonable expectation that the reservoir will maintain water quality within the Massachusetts Water Quality Regulations. While the concept was first formulated for and applied to Quabbin Reservoir, it can be applied to all reservoirs because it is essentially a categorical constraint on the determination of reservoir safe yield.

The minimum pool concept implies that, on the basis of specified water quality considerations, it may not be permissible to use the otherwise available flood or water supply storages for consumption. Thus, under the minimum pool concept, the safe yield of a reservoir may be substantially less than the safe yield as historically determined on the basis of water quantity alone.

Key Considerations

Various regulatory, operational and scientific issues must be considered in any application of the minimum pool concept.

First, as originally formulated, the major criterion for determining the minimum pool level is compliance with "state water quality regula-

tions". Water quality regulations vary from state to state. Also, some regulations pertain to public health standards applied to waters within the reservoir; others apply to public health standards for waters in the distribution system; and others apply to public health standards for waters delivered at the tap. Still other regulations involve public welfare standards (e.g., aesthetics, recreation) and environmental standards (e.g., nutrients, viable fisheries, etc.). The complexity of state and federal water quality regulations (as well as advisory criteria and guidelines) is discussed in Chapter 3. It is sufficient to note here that any application of the minimum pool concept requires a precise statement of regulatory requirements and objectives.

Second, the vast majority of water quality regulations, criteria or guidelines do not specify the precise location, time, or frequency with which reservoir or distributed waters must meet water quality standards. Thus, the criterion, "compliance with water quality regulations", requires a precise statement of methodological requirements for the monitoring and analysis of water quality.

Third, compliance or non-compliance of reservoir water quality to some standards is a moot question in those instances in which withdrawn reservoir waters are processed in water treatment facilities prior to entry into the distribution system. Thus, any practical use of the minimum pool concept requires consideration of the treatment capability and efficiency of any on-line or proposed treatment facility.

Fourth, the minimum pool concept requires projections of water quality as a result of reservoir drawdown. However, water quality in a

lacustrine ecosystem is influenced by an extremely large number of biotic and abiotic factors which interact in spatially and temporally complex ways. According to Wetzel (1975), "if we really scrutinize the existing information in an unbiased way, the only conclusion is that we remain quite ignorant of the complex operation of these interactions". The inabilty of limnologists to apply precise understanding of lacustrine ecosystems for the purpose of making accurate predictions of changes in ecosystem dynamics or water quality is emphasized by a large number of investigators, including Ackermann _et al_. (1973), Goldman (1974), Symons (1969), Baxter (1977), and McAfee (1980). While there are well over 200 computerized models of lacustrine ecosystems (Zison _et al_., 1978; Medina, 1979; Grimsrud _et al_., 1976; Lehmann, 1975), none of these models is sufficient for predicting precise ecological and/or water quality fluctuations in a lacustrine system over extended periods of time. This is particularly true with respect to the relatively large number of water quality parameters typically included within state regulations pertaining to water supply reservoirs. Thus, any use of the minimum pool concept must be based on an understanding of the current limitations of limnological theory and understanding.

Minimum Pool Concept and Environmental Assessment

Since 1970, the integration of regulatory, operational and scientific considerations for the purpose of making decisions that affect natural resources and the public has become formalized under the general term, "environmental assessment process". The environmental assessment process

varies with legal jurisdiction, including jurisdiction of the National Environmental Policy Act or similar state environmental policy acts, the Clean Water Act and other Federal and state legislation and Executive Orders.

Regardless of the specific regulatory authority for environmental assessment in a particular case, a key aspect of all environmental assessments is the comparison of the projected environmental consequences of a proposed action with the projected environmental consequences of no action (the so called, "no-action alternative"). With respect to the minimum pool concept, the proposed action is the imposition of an operational constraint on reservoir pool level which is based solely on water quality considerations; the no-action alternative is to implement no such constraint.

The formative period for environmental assessment in the United States was approximately 1970-1978. In the same period and extending through the present, increased national attention has also been given to what has come to be known as "hazard assessment" and "risk assessment". While the terms risk and hazard have been variously used by different authors, the more consensual meanings are as follows (Lowrance, 1976):

- Hazard Assessment: the determination of the types of physical, chemical and biological dangers to human safety, health and welfare
- Risk Assessment: the determination of the probability and severity with which individuals will actually experience identified hazards

While much attention has been given to the application of hazard and risk assessment considerations and techniques to human health, safety and welfare (Kates, 1978; Burgess, 1981; National Academy of Sciences, 1983; Long and Schweitzer, 1982), there has been an increasing tendency to apply these same considerations to non-human components of the environment as well (Cairns et al., 1978; Dickson et al., 1979; Branson and Dickson, 1981; Mayer and Hamelink, 1977).

The environmental assessment process, inclusive of the historic approaches as defined by the National Environmental Policy Act and the more recent considerations of hazard and risk assessment, helps to define specific steps to be taken in the determination of the minimum pool level for water supply reservoirs. These steps may be summarized as follows:

(1) identify the hazards (public health, safety and welfare as well as environmental) which may be associated with water supply reservoirs,

(2) Assess the risks to human consumers and lacustrine biota which may be associated with the drawdown of reservoir pool levels,

(3) Compare the risks to human consumers and lacustrine biota which may be associated with partial and total drawdowns to the lowest reservoir outlet, and

(4) Recommend operational constraints on reservoir pool levels to achieve specified water quality objectives.

CHAPTER 3

REGULATORY INPUTS INTO THE MINIMUM POOL DETERMINATION

Nomenclature

The technical and regulatory literature pertaining to water quality contains numerous examples of different uses of key terms, including "water quality", "water quality criterion", "water quality standard", "water quality regulations" and "water quality guidelines".

For example, White (1971) notes: in 1908, the Inland Waterways Commission considered water quality only in terms of manufacturing needs and human health; in 1909, the National Conservation Commission considered water quality only in terms of navigational needs; in 1914, water quality was gauged primarily with respect to bacteriological contaminants in water; and only in 1925 did chemical and physical parameters begin to come into general use for determining water quality for public health purposes. After reviewing the history of the concept of water quality, White concludes that "it may be argued that clean water is what the public agencies judge the articulate and influential citizen groups are willing to accept, given their perception of the costs and gains entailed".

The Federal Water Pollution Control Act, as amended by the Water Quality Act of 1965 _et seq._, requires that the setting of water quality objectives shall consider the use and value of water for public water supply, propagation of fish and wildlife, recreational purposes and agricultural, industrial and other legitimate uses. Thus, contemporary judgments of water quality must consider a wide range of actual uses of water. This

is a potentially confounding requirement for the application of the minimum pool concept to a reservoir originally designed as a single purpose resource (e.g., domestic water supply) which may evolve into a multipurpose resource (e.g., domestic water supply and a fisheries resource).

The Federal Water Pollution Control Administration (FWPCA, 1968) also noted a diversity of meanings associated with the terms, "criterion" and "standard". Accordingly, the FWPCA suggested the following definitions as appropriate:

- criterion: a scientific requirement on which a decision or judgment may be based concerning the suitability of water quality to support a designated use
- standard: a plan that is established by governmental authority as a program for water pollution prevention and abatement.

These definitions give emphasis to a standard as a legally enforceable water quality objective, and to a criterion as a scientifically based, advisory objective. These meanings are compatible with definitions which have since been promulgated by the U.S. Environmental Protection Agency (1976):

- criterion: designated concentration of a constituent that, when not exceeded, will protect an organism, an organism community, or a prescribed water use or quality with an adequate degree of safety; may be a narrative statement instead of a constituent concentration.
- standard: a legal entity for a particular reach of waterway or for an effluent; may be based on a water quality criterion as a

basis for regulation or enforcement but may differ from that criterion because of prevailing local natural conditions or because of the importance of a particular waterway, economic consideration, or the degree of safety to a particular ecosystem that may be desired.

In keeping with the above current uses of criterion and standard, it is useful to consider that water quality regulations constitute the legally enforceable water quality standards for a particular legal jurisdiction; water quality guidelines constitute non-enforceable, advisory water quality criteria which may be useful for setting water quality objectives without respect to legal jurisdiction.

Significance of Standards and Criteria to Minimum Pool

With respect to the determination of the minimum pool elevation of any reservoir, it is important to consider the following aspects of water quality standards and criteria:

(1) The vast majority of water quality standards and criteria are stated in terms of individual parameters (e.g., total coliform bacteria, nitrate-nitrogen, color, etc.). Thus, in any particular case, reservoir waters may meet certain standards or criteria for a prescribed use and may also simultaneously fail to meet other standards or criteria for that same use.

This suggests that the determination of minimum pool be made on the basis of considering numerous parameters of water quality rather than on the basis of some single or integrative measure of water quality. For

example, during drawdown, concentrations of total coliform bacteria in a domestic water supply may meet the promulgated standard, while concentrations of mercury may not due to drawdown-enhanced resuspension of particulates to which mercury moieties have previously been adsorbed. In this case, a determination of the minimum pool should consider both phenomena and should not be based on either alone.

(2) Some water quality standards and criteria are stated in terms of qualitative objectives. For example, a standard for nutrients may be stated as "not to exceed limits necessary to control eutrophication". Such standards and criteria typically include a variety of assumptions (e.g., that we know all the essential nutrients of each algal species) or require subjective judgments (e.g., judgments as to when a reservoir is or is not eutrophic). This consideration emphasizes that the determination of minimum pool level is not a totally objective determination. It includes subjective evaluations and judgments as well as objective scientific assessments.

(3) The historical development of standards and criteria demonstrates that they change over time. For example, in 1968 the Federal Water Pollution Control Administration (FWPCA, 1968) included quantitative limits for concentrations of boron and uranyl ion in domestic water supplies; however, these chemical species are not included in the standards for domestic water supplies promulgated by the U.S. Public Health Service in 1962 or by the U.S. Environmental Protection Agency in 1976. Also, concentrations for chloride, sulfate, copper, iron, manganese and zinc promulgated by the FWPCA as desirable limits for public water supplies are

currently included only as "secondary standards" (i.e., non-enforceable) by the EPA. Finally, the range of permissible pH values promulgated by the FWPCA in 1968 is 6.0-8.5 pH Units; the range promulgated by EPA is currently 6.5-8.5 pH Units, and is included only as a secondary standard. Promulgated standards with respect to aquatic wildlife also varied in the period 1968-1976, including standards with respect to concentrations of carbon dioxide and nutrients, color, turbidity and pH.

In light of historical changes in water quality criteria and standards, any determination of a minimum pool has at best only temporal validity. Verification of original estimates should therefore be made (e.g., by means of water quality monitoring) over the operational lifetime of the reservoir to ensure compliance with developing standards and criteria.

Federal and State Regulations

In his review of the various approaches taken at Federal and state levels to achieve water quality objectives, White (1971) notes that there are several advantages to both procedural and technical ambiguities in water quality regulations, including:

- enhancement of administrative discretion in the application and enforcement of standards
- enhancement of flexibility in standards from time to time and place to place as needs, perceptions and technology change

While ambiguities in water quality regulations may in fact provide important administrative advantages with respect to the achievement of

water quality objectives in a diverse and complex nation, certain ambiguities in Federal and state regulations require careful consideration in the application of the minimum pool concept to a specific reservoir.

The National Interim Primary Drinking Water Regulations established maximum contaminant levels (MCLs) in regulated water supplies for a variety of physical, chemical, biological and radiological substances or matter (U.S. Environmental Protection Agency, 1977). Maximum contaminant levels pertain to the free flowing outlet of the ultimate user, except in the case of turbidity where the MCL is measured at the point of entry to the distribution system. In attempting to determine a minimum pool level, there are a number of practical ambiguities with respect to MCLs which must be resolved on a reservoir by reservoir basis.

For example, a given reservoir may be interconnected with a series of distribution reservoirs. Drawdown in an upstream reservoir may result in increases (in excess of MCLs) in turbidity and other contaminants at the output from the upstream reservoir. However, the lowest downstream reservoir prior to the distribution system leading to the "free flowing outlet of the ultimate user" may dilute the turbidity from the upstream reservoir so that outflows from the downstream reservoir meet the MCL for turbidity. Other combinations of dilution and concentration effects due to multi-reservoir operations are, of course, possible. It is also possible that one outlet from a reservoir leads directly to a "free flowing outlet of the ultimate user" and that another outlet leads to a series of downstream distribution reservoirs. In such cases, the minimum pool determination must proceed from decisions to consider specific MCLs at specific outlets

and/or reservoirs.

Extensive groundwater infiltrations in distribution systems also require careful consideration in the determination of a minimum pool which will meet the water quality requirements of the Safe Drinking Water Act. For example, while reservoir drawdown may result in waters which violate MCLs, so may short- and long-term fluctuations in the quality of water infiltrating distribution systems emanating from that reservoir. In determining the minimum pool level it is therefore necessary to decide whether or not to consider infiltrations into distribution systems as well as reservoir dynamics in the estimation of water quality at the "free flowing outlet of the ultimate user".

As pointed out in Chapter 2, the vast majority of state regulations do not specify the location in a reservoir, depth of water, time of day or year, or frequency at which water quality parameters shall be monitored for compliance with water quality standards. These are particularly troublesome ambiguities in the regulations when it comes to determining the minimum pool of an actual reservoir.

For example, some state regulations require a dissolved oxygen content of 6.0 mg O/1 for waters supporting cold water fisheries. However, waters having 6.0 mg O/1 between 10:00 AM and 2:00 PM on a sunny summer day may also have substantially less than 6.0 mg O/1 at 4:00 AM. Thus it is necessary, in light of such ambiguities in the stated standard, to consider the objective of the standard (e.g., maintenance of cold water fisheries) and, possibly, to factor that objective into the minimum pool determination more precisely than the standard itself.

The importance of considering the overall objectives of standards rather than the stated standards themselves is even more pronounced in light of the natural water quality treatment processes that occur in any reservoir. Thus, violations of certain water quality standards at some locations in the reservoir as a result of drawdown might be ignored due to the natural treatment capacity of the reservoir. While there is no universally accepted measure of an integrated physical, chemical and biological treatment capacity of a reservoir, some consideration of the basic dynamics of natural treatment (from input to output of reservoir waters) is necessary in the determination of minimum pool elevation.

Regulations, Hazards and Risks

Water quality regulations (Federal and state) essentially perform two tasks: they identify the potential source or indicator of a variety of hazards and they seek to set a limit to risks. Within any specific regulation, the source or indicator of public health, safety and welfare and environmental hazard is the specified water quality parameter, and the acceptable risk is factored into the quantitative or qualitative limit associated with the specified parameter.

The known hazards and risks which underlie any water quality regulation are always limited by the state of scientific knowledge. As stated by the U.S. Environmental Protection Agency in that agency's "philosophy of quality criteria" (EPA, 1976),

> Criteria are presented for those substances that may occur in water where data indicate the potential for harm to aquatic life, or to water users, or to the consumers of the water or of the aquatic life. Presented criteria do not represent an all-

inclusive list of constituent contaminants. Omissions from criteria should not be construed to mean that an omitted quality constituent is either unimportant or non-hazardous.

The practical consequence of this caveat to the determination of a minimum pool elevation is that, while compliance with water quality regulations may be the key criterion for that determination, compliance does not ensure that waters at or above the minimum pool level will be free from hazard or present zero risk to either the human consumer or to lacustrine biota.

This limitation to any determination of a minimum pool means that such a determination represents a "best effort" to recognize known hazards and to minimize known or perceived risks. The "best effort" approach to a determination of a minimum pool elevation is consistent with approaches taken in various types of contemporary environmental assessments, including environmental assessments mandated by the National Environmental Policy Act and the Clean Water Act.

A "best effort" approach in any type of environmental assessment does not preclude the use of experimental techniques which may fill in key data gaps or expand current understanding of environmental phenomena. However, the use of experimental techniques in a "best effort" environmental assessment is typically highly constrained by time, personnel and costs and by numerous other technical, political and legal requirements of the deicsion-making process in Federal and/or state agencies. Generally, laboratory, field and/or numerical modeling experiments are considered only when (1) the information sought is not available or cannot be extrapolated from the published literature, (2) the information is considered critical

for purposes of agency decision-making, and (3) there is substantial agreement that the proposed experiments will in fact provide the required information in a timely and cost-effective manner (Erickson, 1979).

Such severe constraints on the use of experiments in the determination of a minimum pool elevation essentially preclude the comprehensive use of experiments on a reservoir to reservoir basis which are relevant to a wide range of potential (human and environmental) hazards and risks.

For example, the U.S. Environmental Protection Agency (1977) has identified a number of well recognized phenomena which relate directly to the development of environmental criteria but which are understood only imprecisely and cannot now be factored into water quality criteria in any but a rather superficial manner, including:

- interspecies interactions
- interrelationships among sediments and constituents of overlying water
- antagonistic and synergistic reactions among water quality constituents
- chronic as well as acute effects of water quality constitutents on aquatic biota

It is highly improbable that the "best effort" determination of the minimum pool for any reservoir will be based on results of extensive experiments specifically designed to provide definitive information on the effects of the drawdown of that reservoir on these phenomena and on related water quality parameters.

Water Quality Data Base

In lieu of comprehensive experiments specifically undertaken to provide definitive data for a particular reservoir, any determination of a minimum pool will most likely be based on data which exist at the time of the determination of the minimum pool elevation.

Due to the highly variable sources of available data, the data base is typically limited by the following sources of variation:

- differences in parameters measured, in frequency and timing of sampling, and in sampling locations, depending on the different research objectives of different studies and/or on changing objectives within any single, long-term study
- differences in field and/or analytical methodologies from study to study and/or within a single study over time
- differences in formats and styles of written reports, which influence the availability of raw data and/or limit the scientific value of processed data

In light of these considerations, it is evident that any determination of a minimum pool elevation must be based on a careful evaluation of the existing water quality data base. This evaluation must include consideration of the internal consistency and comparability of the data and of the relevance of the data to reservoir drawdown.

CHAPTER 4

CRITERIA FOR ASSESSING EFFECTS OF RESERVOIR DRAWDOWN

Approach

A substantial literature exists on the effects of water level on the water quality and on other ecological attributes of lacustrine ecosystems. However, the relevance of the published information to any determination of a minimum pool level for a water supply reservoir is highly limited for three reasons.

First, much of the published literature on the consequences of manipulating water levels focuses on the construction of dams and new impoundments along large rivers and on the effects of this construction on impounded and downstream waters. Thus, these studies do not relate directly to a minimum pool determination for an existing water supply reservoir in which lacustrine dynamics predominate over riverine dynamics. In the case of a minimum pool determination for a newly constructed reservoir, such studies may be useful for projecting baseline water quality conditions (i.e., conditions prior to drawdown). However, it is generally agreed that projections of water quality for a newly constructed reservoir which are made on the basis of observed water quality changes in previously constructed reservoirs are quite poor (Baxter, 1977).

Second, studies of the effects of actual drawdown of water levels typically focus on a single attribute of water quality and/or lacustrine ecology, or on a particular type of impoundment, such as zooplanktonic communities or decomposition of organics in pumped storage reservoirs

(Potter and Meyer, 1982; Potter et al., 1982), micronutrients for blue-green algae in a newly constructed reservoir (Elder et al., 1979), fish and invertebrates in small, cold water reservoirs (McAfee, 1980), or aquatic macrophytes in small, recreational impoundments (Dunst et al, 1974).

Third, the available studies are typically descriptive; they are not experimental and cannot be used to identify cause-effect relationships between fluctuations in water level and water quality.

In the absence of an extensive literature which focuses comprehensively on the effects of drawdown on a wide range of water quality parameters and limnological attributes of various types of water supply reservoirs, it is necessary that any determination of a minimum pool elevation be made according to the following three-step procedure:

(1) Determine if historic fluctuations in water level in the subject reservoir can be associated with fluctuations in water quality or environmental parameters that are included in the appropriate water quality standards,

(2) Identify key drawdown-related phenomena which pertain to appropriate water quality standards and which may also be influenced by changes in reservoir level, and

(3) Evaluate selected key drawdown-related phenomena in light of the water quality, limnological and hydrologic data base of the subject reservoir.

Associations between historic drawdowns in water level and changes in water quality do not necessarily indicate that subsequent drawdowns will

result in similar changes in water quality. Thus, the identification and evaluation of key drawdown-related phenomena (Steps 2 and 3, above) are necessary steps even in those cases in which historic drawdowns and hypothesized effects on water quality can be documented.

Key Drawdown-Related Phenomena

Key drawdown-related phenomena are those phenomena which meet the following requirements:

(1) They relate directly to drawdown of reservoir level,

(2) They have important roles in the dynamics of water quality constituents or ecological processes, and

(3) They are associated with the universe of water quality attributes which are included in relevant water quality regulations.

For purposes of this discussion, the following five drawdown-related phenomena are proposed:

- wind-mediated disruption of thermal stratification (i.e., destratification)
- light penetration to benthic habitat (including exposure of benthic habitat)
- reduction in the transit time of water masses (or residence time) within the reservoir
- increase in hypolimnetic temperature
- mechanical stirring of bottom sediment

Potential relationships of these drawdown-related phenomena to some parameters typically included in state water quality regulations are

included in Table 1.

A water quality parameter may be affected by more than one drawdown-related phenomenon. Also, any parameter may be directly as well as indirectly affected by the same drawdown-related phenomenon. For example, destratification during the summer may result in the mixing of well oxygenated, epilimnetic waters with relatively poorly oxygenated hypolimnetic waters and thereby directly result in an increase in hypolimnetic oxygen. However, destratification may also result in the mixing of nutrient-rich bottom waters with relatively nutrient-deficient surface waters. This may, in turn, lead to an increase in photosynthesis by phytoplankton in the epilimnion, a subsequent die-off of enhanced phytoplanktonic densities in the epilimnion, and finally an enhanced oxygen demand in hypolimnetic waters due to the decomposition of settled algal biomass.

Another important consideration is that a particular water quality parameter may be affected by drawdown but may also, in turn, influence other effects of drawdown. For example, light penetration to benthic habitat (as a result of drawdown) may result in the enhanced growth of benthic algae or macrophytes which utilize nutrients otherwise sequestered in bottom sediments. Upon the death of these organisms (or through excretion of cellular materials) nutrients contained in their biomass may be released to the water and may be utilized by phytoplankton. However, dense populations of phytoplankton may in turn reduce the light transmissivity of water and thereby reduce the amount of light at the bottom of the reservoir and thus the density of benthic plants utilizing nutrients in the sediments.

Table 1

Examples of Water Quality Standards Potentially Influenced by Drawdown-Related Phenomena

State Water Quality Standard*	Destratification	Light Penetration to Benthic Habitat	Reduction in Transit Time	Increase in Hypolimnetic Temperature	Mechanical Stirring of Bottom Muds
Dissolved Oxygen	+	+	+	+	+
Temperature	+	+	+	+	
pH	+	+	+	+	+
Total Coliform Bacteria			+		
Turbidity	+	+	+	+	+
Total Dissolved Solids			+		+
Chlorides			+		
Sulfates			+		+
Nitrate	+	+	+	+	+
Aesthetics		+	+		+
Radioactive Substances					+
Color	+	+	+	+	+
Total Suspended Solids		+	+	+	+
Oil and Grease			+		
Nutrients	+	+	+	+	+
Metals and Organics					+

*Examples of standards are from the Massachusetts Water Quality Regulations (MDEQE, 1977 et seq.).

Note: A blank in the table indicates that there is no major influence of the drawdown-related phenomenon on the water quality standard.

Evaluation Criteria

For purposes of this discussion, evaluation criteria are selected for water quality and hydrologic parameters or categories of parameters which, in the case of a specific reservoir, fulfill the following requirements:

(1) There is a quantitative data base for these parameters for the subject reservoir,

(2) These parameters relate to appropriate water quality standards and/or criteria,

(3) Historic data for these parameters are available for any periods in which there are recorded major fluctuations in the water level of the reservoir, and

(4) Fluctuations in the values of biological, physical and/or chemical parameters can be influenced by one or more of the key drawdown-related phenomena discussed above.

Examples of biological, chemical and physical evaluation criteria are included in Tables 2, 3 and 4. Hydrologic evaluation criteria include stage-volume relationships, magnitude and frequency of rainstorm events and peak flows in watershed drainages. It is assumed that the hydrologic criteria may be related to all water quality standards but may not be influenced by any of the key drawdown-related phenomena.

In cases where the subject reservoir has undergone major fluctuations in water level, the historic data base for evaluation criteria prior to and following those fluctuations may be assessed to determine potential influences of water level on water quality and project a minimum pool level. However, note that any association noted between fluctuations in

Table 2

Examples of Biological Evaluation Criteria for the Determination of Minimum Pool Level

Evaluation Criteria	State Water Quality Standards Related to Criteria*	Drawdown-Related Phenomena Potentially Influencing Criteria
Phytoplankton	• Aesthetics • Color • Nutrient • Nitrate • Dissolved Oxygen • pH • Turbidity	• Summer Destratification • Light Penetration to Benthic Habitat
Total Coliform Bacteria	• Total Coliform Bacteria • Temperature	• Reduction in Transit Time • Increase in Hypolimnetic Temperature
Fish	• Temperature • Dissolved Oxygen • pH • Aquatic Habitat	• Increase in Hypolimnetic Temperature • Summer Destratification • Mechanical Stirring of Bottom Muds • Light Penetration to Benthic Habitat
Littoral Vegetation	• Turbidity • Aesthetics • Nitrate • Nutrients • Color	• Light Penetration to Benthic Habitat

*Note: Water Quality Standards refer to Massachusetts Water Quality Regulations (MDEQE, 1977 *et seq*.).

Table 3

Examples of Chemical-Physical Evaluation Criteria for the Determination of Minimum Pool Level

Evaluation Criteria	State Water Quality Standards Related to Criteria*	Drawdown-Related Phenomena Potentially Influencing Criteria
Turbidity	• Turbidity • Aesthetics • Color • Total Suspended Solids • Temperature	• Reduction in Transit Time • Mechanical Stirring of Bottom Muds • Light Penetration to Benthic Habitat • Summer Destratification
Color	• Color • Aesthetics	• Reduction in Transit Time • Summer Destratification • Light Penetration to Benthic Habitat
Nutrients	• Nitrate • Nutrients • Turbidity • Dissolved Oxygen	• Reduction in Transit Time • Mechanical Stirring of Bottom Muds • Light Penetration to Benthic Habitat • Summer Destratification • Increase in Hypolimnetic Temperature
Metals	• Metals	• Mechanical Stirring of Bottom Muds • Reduction in Transit Time
Miscellaneous	• Dissolved Oxygen • Organics • Temperature • Aquatic Habitat	• Increase in Hypolimnetic Temperature • Mechanical Stirring of Bottom Muds • Light Penetration to Benthic Habitat • Summer Destratification

*Note: Water Quality Standards refer to Massachusetts Water Quality Regulations (MDEQE, 1977 *et seq.*).

Table 4

Examples of Physical Evaluation Criteria for the Determination of Minimum Pool Level

Evaluation Criteria	State Water Quality Standards Related to Criteria*	Drawdown-Related Phenomena Potentially Influencing Criteria
Thermal Stratification	• Dissolved Oxygen • Temperature • pH • Nitrate • Nutrients • Aquatic Habitat	• Summer Destratification • Light Penetration to Benthic Habitat • Increase in Hypolimnetic Temperature
Transit and/or Residence Time	• Dissolved Oxygen • Total Coliform Bacteria • Turbidity • Color • Total Suspended Solids	• Reduction in Transit Time
Temperature of Reservoir Strata	• Dissolved Oxygen • Temperature • Aquatic Habitat • Aesthetics	• Summer Destratification • Light Penetration to Benthic Habitat • Increase in Hypolimnetic Temperature
Shoreline and Sediment Exposed to Light	• Nutrients • Nitrate • Color • Turbidity • Dissolved Oxygen • Temperature • Aesthetics	• Light Penetration to Benthic Habitat

*Note: Water Quality Standards refer to Massachusetts Water Quality Regulations (MDEQE, 1977 et se.).

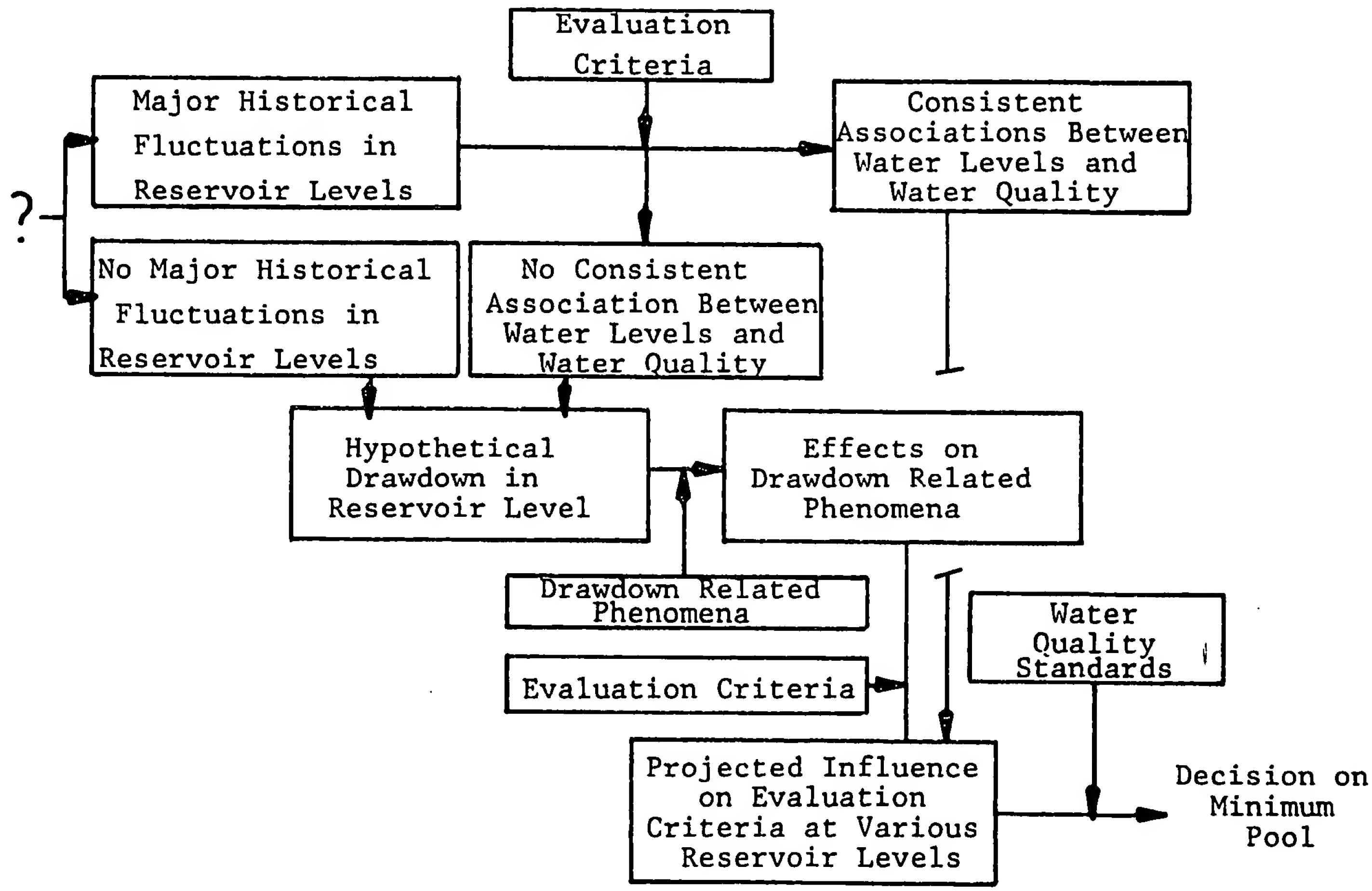
Even should a causal relationship between water level and water quality be demonstrated by means of data collected in periods of historic drawdown, projections of water quality under future drawdown levels are at best highly tenuous. This is because the large number of water quality constituents and their complex interactions undermine any assumption that a specific functional association will be linear or even continuous over all possible reservoir levels.

In cases where no major fluctuations in water level have occurred or where no functional relationships between observed fluctuations in water level and evaluation criteria can be determined, it is necessary to assess the effects of hypothetical drawdowns on the key drawdown-related phenomena and thence on the evaluation criteria and related water quality standards. The overall approach is depicted in Figure 1.

As indicated in Figure 1, the use of the same evaluation criteria in both fluctuating and non-fluctuating reservoirs allows for a direct comparison of projected water quality impacts of both actual and hypothetical fluctuations in reservoir level. However, the projection of water quality impacts under hypothetical drawdown conditions requires the consideration of (a) the effect of drawdown on identified drawdown-related phemonema (see above) and (b) the potential influence of these phenomena on selected water quality parameters (i.e., evaluation criteria). While some projections of effects on drawdown-related phenomena can be tested by means of a variety of established algorithms, projections of subsequent impacts on individual water quality parameters or evaluation criteria are highly constrained by our currently limited quantitative knowledge and understanding of a large number of limnological processes.

Figure 1

Overview of Approach to Determination of the Minimum Pool Level



CHAPTER 5

CASE STUDY: DATA BASE FOR QUABBIN RESERVOIR

Introduction

Quabbin Reservoir (Figure 2) is the primary water supply for over two million persons in the metropolitan Boston area. It was created by damming three branches of the Swift River. Construction of dams was completed in 1939. Diversion of Ware River waters into the reservoir began in 1940 and the reservoir first attained maximum volume (412 billion gallons) in 1946. Primary withdrawal of water is through Shaft 12 which connects to the Quabbin Aqueduct. This aqueduct conducts withdrawn waters (610 MGD capacity) for about 25 miles east to Wachusett Reservoir; waters withdrawn from Wachusett Reservoir first enter a series of aqueducts and then the distribution system for the metropolitan Boston area.

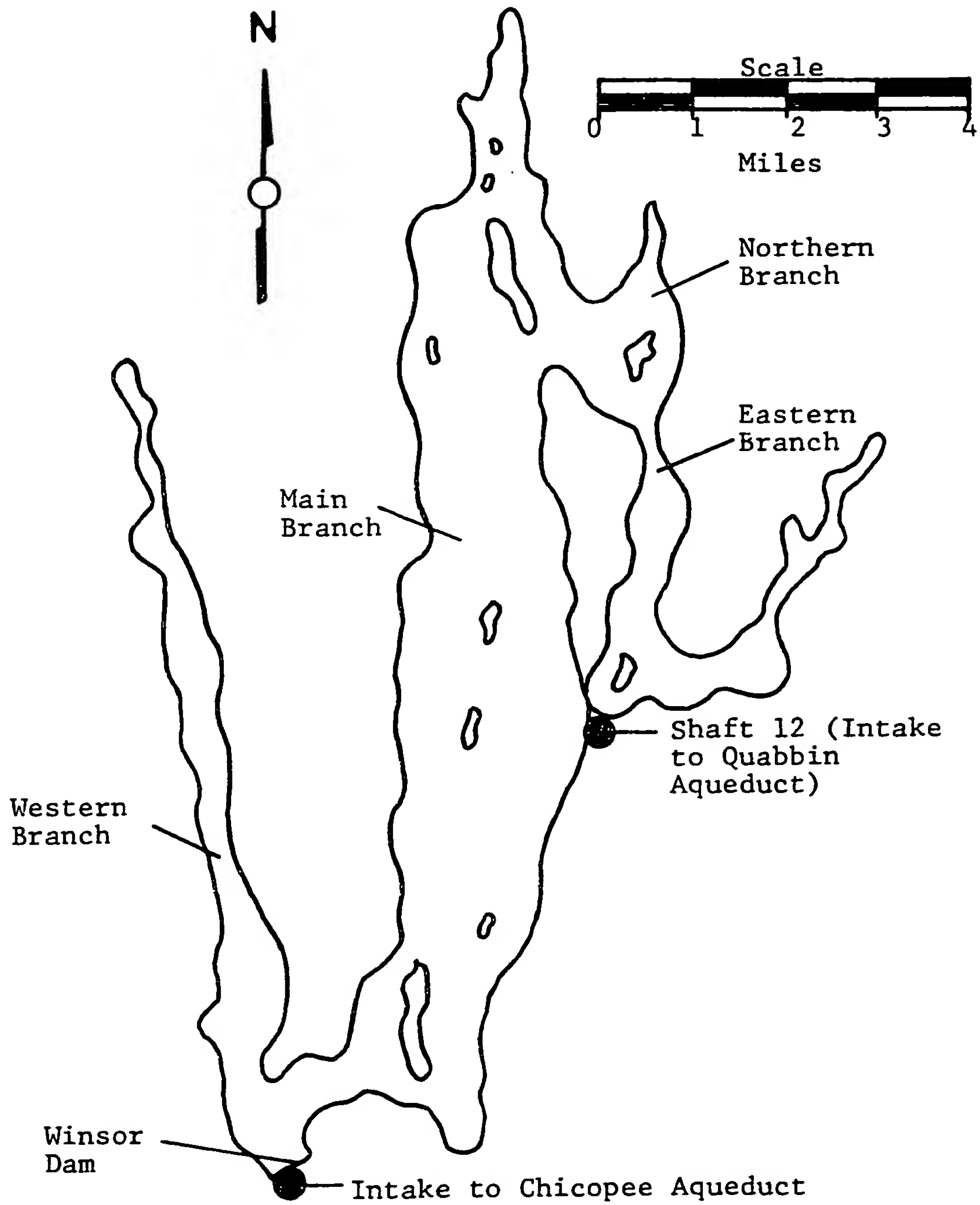
At full pool, the surface area of Quabbin Reservoir is about 39 square miles; the mean and maximum depths are 50 ft. and 150 ft., respectively; the length of shoreline (including islands) is approximately 165 miles, and shoreline development is 7.4.

Hydrologic Data Base

For the purpose of determining the minimum pool level, key hydrologic data include precipitation data, changes in reservoir elevation and high flow episodes. These data were obtained from the National Oceanic and Atmospheric Administration (NOAA) for Westover Air Force Base, and the Metropolitan District Commission (MDC).

Figure 2

Quabbin Reservoir



Precipitation

Annual precipitation in the Quabbin watershed in the period 1955-1982 is summarized in Figure 3. Precipitation for the period 1961-1971 was below average; for eight of these years, it was substantially below average. In contrast, there were seven years during the 1970's in which precipitation was above average and, for four of these years (1972, 1975, 1977 and 1979), it was substantially above average (Hellstrom, 1982).

Changes in Reservoir Elevation

During the period 1940-1982, Quabbin Reservoir underwent several major changes in surface elevation (Figure 4). The first and largest was that which occurred during the period 1940-1946, the time of initial filling of the reservoir.

The reservoir undergoes a normal fluctuation in elevation each year. However, for the period 1946-1956, the reservoir was at or near full pool elevation (530 feet). For the next 2-3 years it experienced a small decrease in elevation and did not reach full pool. Following a brief recovery to full pool in 1960-1961, Quabbin Reservoir experienced progressively lower elevations in the mid-1960's. This is the well-recognized period of the New England drought (see precipitation data, above) in which the reservoir was considerably below full pool elevation. The lowest elevation reached during this period was 495.7 ft. in 1967 (about 44% of capacity). During the late 1970's the reservoir again achieved 100% capacity.

Figure 3

Annual Precipitation in Quabbin Reservoir Watershed, 1955-1981

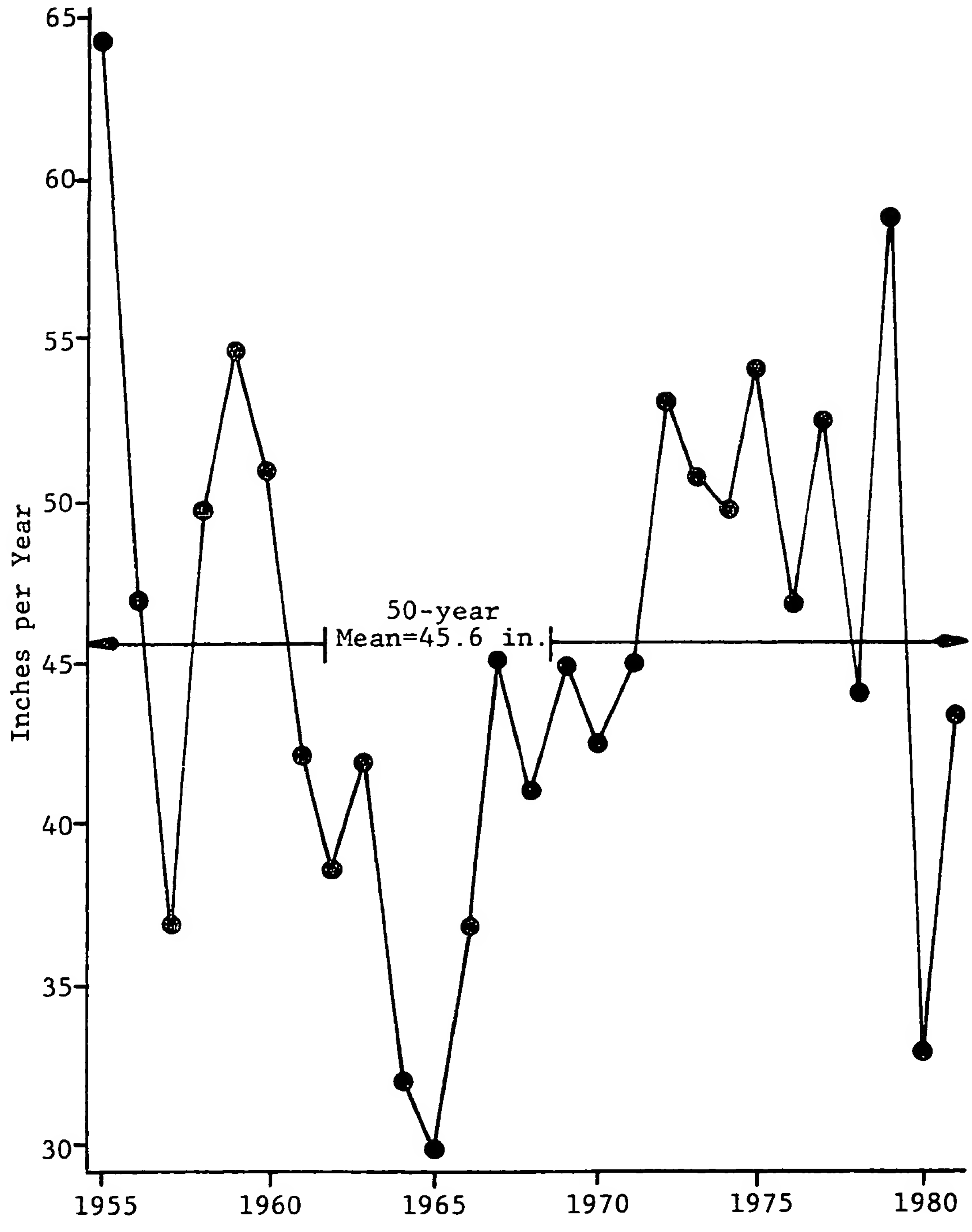
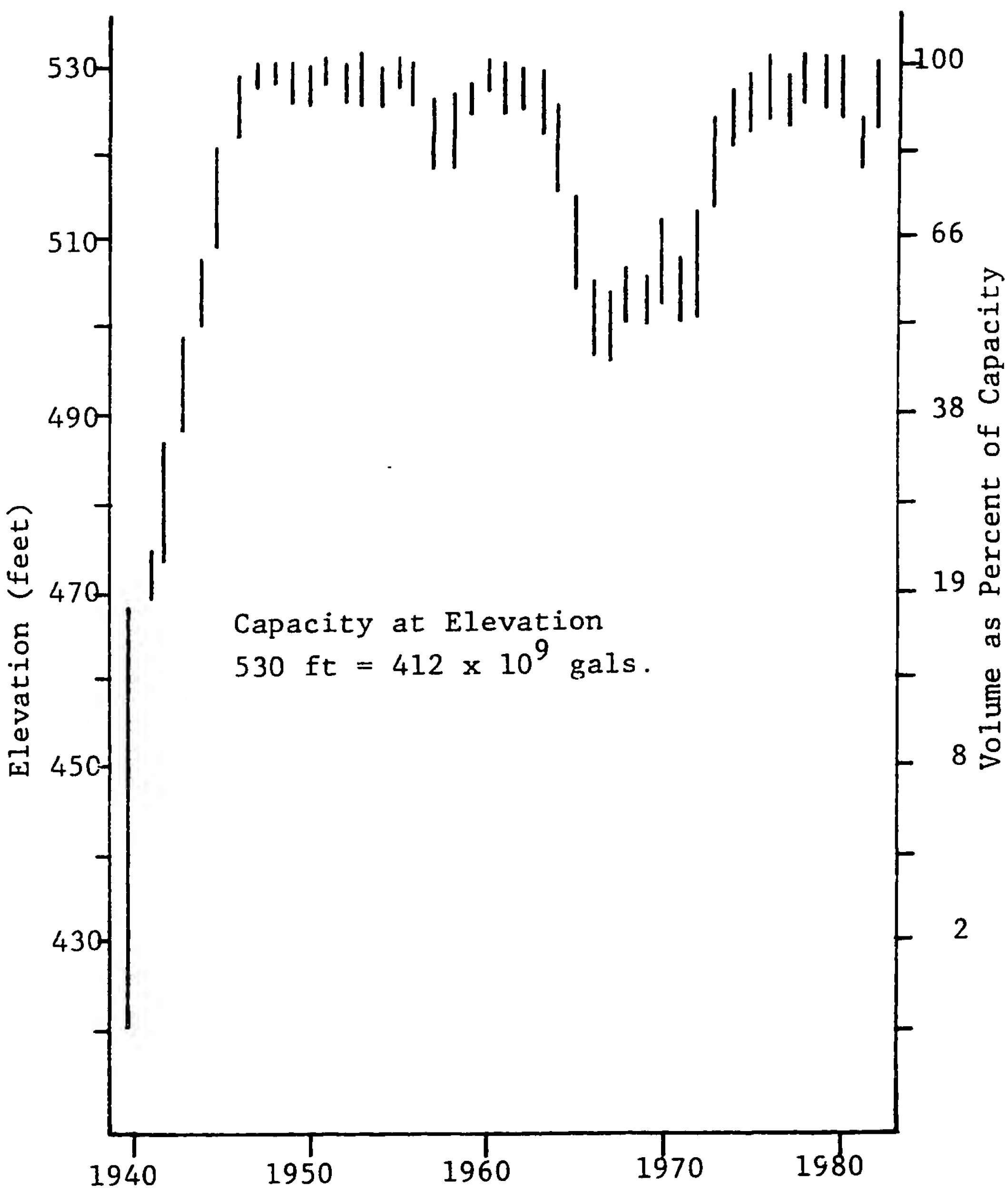


Figure 4

Elevation at Quabbin Reservoir, 1940-1982



High Flow Episodes

Precipitation in central Massachusetts shows large fluctuations over relatively long periods of time. Variations in precipitation result in variations in stream flows in the Quabbin watershed. Stream flow data indicate that the relatively higher flows are normally associated with the spring season. However, they also show that major increases can occur in maximum daily flows in the streams during the months of June, July, August and September.

Any criterion for a major increase in precipitation is arbitrary. For purposes of this analysis, it is assumed that an increase which essentially doubles the 50-year mean monthly precipitation is a major increase. Based on this criterion, the following are the years from 1930 to 1979 which resulted in major increases in precipitation during the months of June through September:

June	July	August	September
1938	1938	1931	1933
1944	1945	1952	1934
1945	1958	1955	1938
1968	1959	1979	1954
1972	1960		1974
			1975

As indicated, periods of high precipitation occurred in every decade from the 1930's to the 1970's. The fewest events occurred during the drought in the 1960's. At least two of these months of high precipitation resulted from major hurricanes (August 1955; September 1938).

Similar assessments can be made of the stream flow data for the Quabbin watershed. For example, an assessment of the maximum daily flows in the East Branch of the Swift River (Hellstrom, 1982) indicates major fluctuations during the summer months. Very large flow episodes occurred in every decade from the 1930's to the 1970's. The three largest flows occurred during three different months and years (June 1944; August 1955; September 1938).

The data on monthly precipitation and maximum daily stream flows in the Quabbin Reservoir watershed indicate that:

(1) High flow episodes during the summer months have occurred in every decade from the 1930's through the 1970's,

(2) These high flow episodes can occur in any month during the summer, and

(3) Several such high flow episodes are likely to occur in the period June-September in each decade.

Biological Data Base

The biological data base includes data on the phytoplankton, total coliform bacteria, fish and littoral vegetation.

Phytoplankton

The Metropolitan District Commission (MDC) conducted surveys of the phytoplankton of the reservoir at a depth of 0-5 feet at various locations in the period May-October 1940. Enumeration of phytoplankton was made by direct microscopic counts recorded in Standard Areal Units per ml. Counts

reported in terms of Standard Areal Units may be higher or lower than counts of whole plankters, depending upon the size distribution of plankters (Sinclair, 1975). Thus, counts reported by the MDC in these early studies cannot be directly compared with counts of whole plankters obtained in more recent studies.

Throughout the period June-July 1940, diatom species (e.g., Asterionella sp. and Tabellaria sp.) accounted for more than 90% of the density of the total phytoplankton. Mean densities of diatoms in the vicinity of the Quabbin and Chicopee aqueducts were 1,204 and 1,615 Standard Areal Units/ml, respectively. In August and September, the diatoms decreased markedly, and blue-green algal species (e.g., Anabaena sp. and Aphanizomenon sp.) became dominant. Mean densities of blue-green populations in the vicinity of the Quabbin and Chicopee aqueducts at this time were 35 and 19 Standard Areal Units/ml, respectively.

Spencer (1950) conducted a comprehensive survey of the phytoplankton of the reservoir in May-October 1948. This survey was conducted at 38 locations in the eastern, northern and main branches of the reservoir. Duplicate samples for each of four depths within the first meter of the water column were collected weekly from 10 randomly selected locations among the total of 38 locations. Samples were pooled to yield 2 duplicate composite samples per location. Enumeration of phytoplankton was made by direct microscopic counts. Triplicate counts were made of each of the 2 composited samples. These counts were averaged to yield an average count per location. Average counts for each of the ten locations sampled each week were used to compute weekly average counts for the reservoir as a

whole.

The weekly average counts of total phytoplankton in the period June-August 1948 ranged from 166 to 1,013 plankters/ml. The mean of the weekly average of total phytoplankton in this period was 479 plankters/ml. Over the same period, the mean of the weekly averages of the Bacillariophyceae (diatoms), Myxophyceae (blue-green algae) and Chlorophyceae (green algae) were 448, 20, and 17 plankters/ml, respectively. The diatoms typically accounted for more than 90% of the total phytoplankton in June and July, and for 43-85% during August. The blue-green algae accounted for 1-3% of the total phytoplankton in June and July, and for 2-43% during August. The green algae accounted for 1-2% of the total in June and July, and for 5-23% during August. Over the entire study period, diatoms averaged about 80% of the total phytoplankton, the blue-green algae, about 14%, and the green algae, about 5%.

Reynolds and Erickson (1969 and Unpublished Data) conducted a survey of selected taxa of phytoplankton in the period 1966-1968. In these studies, samples were collected at various locations in the western, northern, main and eastern branches of the reservoir. Samples were collected at surface (0-1 meter), thermocline and bottom depths. Enumeration of phytoplankton was made by direct microscopic counts of plankters. In 1966 all major taxa of the phytoplankton were enumerated; in 1967 and 1968, pennate and centric diatoms were not enumerated.

For the period July-August 1966, the densities (95% C.I.) of total phytoplankton in surface samples in the eastern (17 samples), northern (18 samples) and main branches (14 samples) are 372 ± 130, 183 ± 31, and

95 ± 42 plankters/ml, respectively. The Student-Newman Keuls procedure for determining significance (SNK procedure) indicates that the mean summer density in the eastern branch is significantly greater ($p < .05$) than mean summer densities in the northern and main branches. There is no significant difference between the mean summer densities in the northern and main branches.

In this same period, chlorococcoid cells accounted for over 90% of the total phytoplankton in the eastern branch, and for about 40% and 30% of the total phytoplankton in the northern and main branches, respectively.

Cell counts of chlorococcoids for the period July-August 1966-1967 were pooled for each of the three branches. In this period, at least six samples were collected in each branch each year. The densities of chlorococcoids (95% C.I.) in the eastern (26 samples), northern (24 samples) and main branches (36 samples) are 280 ± 81, 109 ± 39, and 58 ± 15 plankters/ml, respectively. The mean density of the pooled summer densities of chlorococcoids in the eastern branch is significantly greater ($p < .05$) than the mean densities in the northern and main branches. There is no significant difference between the mean densities in the northern and main branches.

New England Research (NER, 1970-1982) conducted a long-term program of monitoring the water quality of Quabbin Reservoir. A portion of the monitoring effort was directed to the enumeration of phytoplankton in surface waters (0-1 meter) of the eastern, northern, main and western branches of the reservoir. Enumeration of phytoplankton was made by

direct counts of plankters. In the period July-August 1971-1976 the frequency of sampling for phytoplankton was at least monthly, sampling was continuous from year to year, and sampling was conducted at the same location in each of the major branches of the reservoir.

The frequency of sampling in this period was typically low (i.e., 1/month). Data obtained from each branch were therefore pooled for the six-year period. The densities (95% C.I.) of total phytoplankton in surface samples in the eastern (10 samples), northern (13 samples), main (12 samples) and western branches (14 samples) are 195 ± 136, 151 ± 91, 125 ± 48, and 78 ± 46 plankters/ml, respectively. In the same period, the densities of chlorococcoid plankters in the eastern, northern, main and western branches are 107 ± 94, 95 ± 93, 53 ± 30, and 39 ± 36 plankters/ml, respectively. Analysis of variance (ANOVA) was performed on the pooled data. This test indicates that there is no significant difference among the means of total phytoplankton in each branch or among the means of chlorococcoid plankters in each branch.

While the above data are too limited to permit any meaningful analysis of yearly changes in densities of phytoplankton, it is possible that the nature of the phytoplanktonic community may have undergone a qualitative change over this six-year period. For example, chlorococcoid plankters ranged from 30 to 79% of the July-August community in the eastern, northern and main branches in 1971-1975. In 1976, chlorococcoid densities ranged from 10 to 25% of the total phytoplankton in these branches.

Total Coliform Bacteria

During the period June-August 1966-1968, the MDC collected 179 surface samples for analysis of total coliform bacteria. Only a summary of these data is available for review in this discussion.

Samples were collected in each of the four major branches of the reservoir. In 1966, the range of densities observed in 61 samples was 0-8 bacteria/100 ml; in 1967, the range in 51 samples was 0-26 bacteria/100 ml; in 1968, the range in 67 samples was 0-48 bacteria/100 ml. These densities are very low for surface waters, even for surface waters within protected watersheds.

In the period April-September 1971-1979, NER (1972-1980) analyzed a total of 249 surface samples for total coliform bacteria. These samples were generally equally distributed among the major branches of the reservoir. All values were well within ranges typically associated with runoff from protected watersheds (Kuznetsov, 1970). At least 50% of all densities observed in each branch over the nine-year period were ≤ 1 bacteria/100 ml. Also, there was no obvious pattern to densities in any branch with respect to year. Data obtained from each branch were therefore pooled for the nine-year period. The densities (95% C.I.) of total coliform bacteria in the eastern (65 samples), northern (65 samples), main (57 samples) and western branches (62 samples) are 21 ± 14, 24 ± 22, 4 ± 3 and 7 ± 7, respectively. There is no significant difference between the means obtained for the eastern and northern branches, or between the means obtained for the main and western branches. Means for the combined eastern and northern branches are significantly greater ($p < .05$) than the means

for the combined main and western branches.

Fish

Quabbin Reservoir has been an important fisheries resource since 1946 when shoreline fishing was first allowed. In the period 1946-1951, only shoreline fishing was permitted; since 1952, shoreline and boat fishing have been permitted in selected areas.

Since 1952, the Massachusetts Division of Fish and Wildlife has implemented three basic fish management programs (Bridges and Hambly, 1971):

(1) Lake Trout and Walleye Program (1952-1960)

(2) Lake Trout, Rainbow Trout and Brown Trout Program (1957-1965)

(3) Lake Trout and Landlocked Salmon Program (1965-1970)

Each of these management programs has included the management of rainbow smelt (Osmerus mordax) the principal forage species for the salmonids. In the period 1953-1954, rainbow smelt were introduced into the reservoir to provide forage for the introduced lake trout. By 1959, the rainbow smelt had established itself in large enough numbers to cause operational problems in the reservoir and was therefore controlled by seining and various chemical control methods. In 1968, the rainbow smelt was reintroduced to support the developing salmonid populations (Bridges and Hambly, 1971).

By the mid-1970's, the cold-water and warm-water fisheries in the reservoir included the following species (MDFG, Undated; Horwitz, 1972):

Cold-Water Species

landlocked salmon (*Salmo salar*)
lake trout (*Salvelinus namaycush*)
brown trout (*Salmo trutta*)
rainbow trout (*Salmo gairdneri*)
rainbow smelt (*Osmerus mordax*)

Warm-Water Species

smallmouth bass (*Micropterus dolomieui*)
largemouth bass (*Micropterus salmoides*)
white perch (*Morone americana*)
rock bass (*Ambloplites rupestris*)
sunfish (*Lepomis sp.*)
chain pickerel (*Esox niger*)
yellow perch (*Perca flavescens*)
black crappie (*Pormoxis nigromaculatus*)
brown bullhead (*Ictaluris nebulosis*)

The attempt to establish the walleye (1952-1960) as a warm-water species in the reservoir failed, and fish management programs have subsequently focused on the management of the reservoir for cold-water species.

According to Bridges and Hambly (1971), about two-thirds of the reservoir volume (at full pool) consists of cold-water habitat (i.e., water which is $\leq$ 21.4°C and which contains $>$ 5.0 mg O/1). Of the various factors which influence the establishment and maintenance of cold-water species in the reservoir, they conclude that the rainbow smelt is the key factor to successfull cold-water fish management in the reservoir.

With respect to the potential effects of reservoir drawdown in the early to mid-1960's on the Quabbin fisheries, Bridges and Hambly suggest that:

(1) Reservoir drawdown reduced the shoal spawning areas of the rainbow smelt and thereby contributed (along with the MDC smelt control effort) to a significant reduction in population density of this forage fish, and

(2) Reservoir drawdown also probably had an important influence on warm-water fish populations by eliminating much of the spawning habitat of largemouth bass. The consequent reduction in largemouth bass was probably the major factor contributing to the enhancement and subsequent domination of smallmouth bass populations in the reservoir.

Littoral Vegetation

During the period 1961-1973, extensive amounts of normally submerged littoral areas became alternately exposed and inundated due to the fluctuating level of Quabbin Reservoir. The maximum amount of exposed area in this period was about 9,000 acres and occurred in early 1967. The average exposed area during the drought period of 1966-1971 was about 6,000 acres. Over the twelve-year period 1961-1973, areas in excess of 3,700 acres were above water level for eight consecutive years (NER, 1973; Miner, 1974).

MacConnell and Spencer (1969) estimated that, in 1968, about 1,300 acres of exposed areas were becoming a mixed forest of aspens, gray birch and eastern cottonwood. They also estimated that an additional 850 acres were regrowing primarily to gray birch with some aspen and willow.

In 1973 NER conducted a series of field surveys primarily in the northern portion of the reservoir (NER, 1973; Miner, 1974). These surveys

indicated that living woody and herbaceous vegetation provided, on the average, about 45% cover in exposed shoreline areas. About 50% of the exposed shoreline was sand. Vegetative litter, logs and stumps provided the remainder of the cover in exposed areas. Grasses and cottonwood species accounted for about one-quarter of the total living vegetation in exposed shoreline areas. Estimates of vegetative biomass and published data on the chemical constituents of plant materials were used to estimate the amount of various nutrients which were present in the vegetative cover of exposed shorelines. Estimates of vegetative biomass and contained nutrients which were inundated as of July 1973 by rising reservoir levels are as follows:

- Total Vegetative Biomas...............14,200 tons
- Nitrogen contained in biomass............142.0 tons
- Phosphorus contained in biomass............14.1 tons

Chemical/Physical Data Base

The chemical/physical data base includes data on turbidity, color, nutrients, metals and miscellaneous data on dissolved oxygen, organic chemicals and radioactive substances. All analytical methods conform to standard methods for the examination of water (APHA et al., 1984).

Turbidity

Reed (1947) reported turbidity values for the reservoir for the period 1940-1946. These values were reported in units of ppm (parts per million), a unit which was based on the visual comparison of test water with

water containing standard concentrations of diatomaceous earth. Early instrumentation developed to quantify turbidity (e.g., the Jackson Candle Turbidimeter) was also based on standardization with suspensions of diatomaceous earth, and the unit was called the Jackson Candle Unit (JCU), the Jackson Turbidity Unit (JTU) or the Jackson Candle Turbidity Number (JCTN) (Pickering, 1976). More recent changes in methodology have involved the replacement of the candle as a light source with incandescent light sources, the use of photocells, and the substitution of formazin for diatomaceous earth as the standard for calibration. Thus, the values reported by Reed cannot be directly compared with turbidity values generated in more recent studies. It is possible, of course, to calibrate current methods against earlier methods. This was not done in this study because the original instrumentation used by the MDC was not available.

According to Reed, turbidity in surface waters in the vicinity of the Quabbin and Chicopee aqueducts consistently declined in the period 1940-1943, from an annual range of about 3-20 ppm to a range of about < 1-2 ppm; from 1943 through 1946, the annual mean turbidity was < 1.4 ppm. Turbidity in bottom waters in the vicinity of the Chicopee aqueduct also declined in the period 1940-1943, from a range of about 2-14 ppm to a range of about 2-3 ppm; from 1943 through 1946, the annual mean turbidity in bottom waters at this location remained constant at about 2 ppm. Turbidity in bottom waters in the vicinity of the Quabbin aqueduct showed broad annual ranges throughout the seven-year period. For example, in 1940 the annual range was about 3-12 ppm and in 1946, the range was about 1-18 ppm.

Turbidity values generated by the MDC for the period June-Stepember 1966-1967 were consistently low in both surface and bottom waters in the vicinity of the Quabbin and Chicopee aqueducts. All values fell within the range 0.5-3.0 JTU. Quarterly means for each location, depth and year were $\leq$ 1.7 JTU.

Turbidity values for surface waters in the period April-September 1971-1976 (NER, 1972-1977) show no significant differences between means (SNK procedure) for the eastern and northern branches or between means for the northern and main branches in each year. Values obtained from the eastern and northern branches, and values obtained from the main and western branches were therefore pooled for each year. Means of pooled eastern and northern branches and means of pooled main and western branches are significantly different ($p < .05$) for each year. There are no significant differences within each set of pooled values over the six-year period. Turbidity values (95% C.I.) for the pooled eastern and northern branches (96 values) and the pooled eastern and northern branches (94 values) in this period are 0.9 $\pm$ 0.1 and 0.6 $\pm$ 0.1 JTU, respectively.

Color

Reed (1947) reports that, in the period 1940-1943, the maximum color in surface waters was 40 ppm (based on Pt-Co calibration) and, in bottom waters, 195 ppm. The range of annual mean values in this period for surface and bottom waters was about 15-20 ppm and 18-45 ppm, respectively. Annual mean values in surface and bottom waters in 1943-1946 were relatively low (about 10-20 ppm).

In June-September 1966-1967, color values generated by MDC ranged from 4 to 20 Pt-Co Color Units. The mean summer value in surface waters was 5 Pt-Co Color Units; the highest value was 20 Pt-Co Color Units in a single sample collected at a 70-ft. depth.

Color values in surface waters in the period April-September 1971-1976 (NER, 1972-1977) show no significant differences between means (SNK procedure) for the eastern and northern branches or between means for the northern and main branches in each year. Values obtained from the eastern and northern branches, and values obtained from the main and western branches were therefore pooled for each year. Means of pooled eastern and northern branches and means of pooled main and western branches are significantly different ($p < .05$) for each year. Pooled eastern and northern branches show significant differences among means over the six-year period and a significant linear regression (ANOVA) against year ($r^2 = 0.26$; slope = -2.3); this regression also contains substantial variance unexplained by the regression. Pooled main and western branches show significant differences among means but no significant linear regression against year. Pooled values (95% C.I.) in 1971 and 1976 are as follows:

- pooled eastern and northern brances

    1971 (16 values)......18.4 ± 3.4 Pt-Co Color Units
    1976 (16 values)...... 7.3 ± 2.6

- pooled main and western branches

    1971 (14 values)...... 3.7 ± 0.8
    1976 (16 values)...... 4.5 ± 1.2

Nutrients

In the period 1971-1976, NER (1972-1977) analyzed surface samples in each branch of the reservoir for nitrate + nitrite and total phorphorus. Analyses were performed monthly.

There are no significant differences among means (SNK procedure) of concentrations of nitrate + nitrite in the four branches for each of the six years. Values obtained from each branch were therefore pooled for each year. These values (95% C.I.) are as follows:

1971 (56 values)......0.081 ± 0.006 mg N/1
1972 (37 values)......0.054 ± 0.007
1973 (52 values)......0.028 ± 0.006
1974 (52 values)......0.021 ± 0.004
1975 (52 values)......0.041 ± 0.013
1976 (48 values)......0.103 ± 0.031

There are significant differences ($p < .05$) among the means (SNK procedure) obtained in three periods: 1971, 1972-1975 and 1976. Approximately 33% of all values obtained in 1973-1975 were at or below the detection limit (0.01 mg N/1) of the analytical method used for the determination of nitrate + nitrite. For computational purposes, values reported as < 0.01 mg N/1 were considered as 0.01 mg N/1. Thus, the confidence intervals reported above for 1973-1975 are artificially high and may be significantly lower than the confidence interval for 1972.

There are no significant differences (SNK procedure) among means of concentrations of total phosphorus in the four branches for each of the six years. Values obtained from each branch were therefore pooled for each year. There are significant differences ($p < .05$) between means for

pooled values in 1971-1972 and 1973-1976, but not between the means for 1971 and 1972, and not among the means for 1973, 1974, 1975 and 1976. Values for total phosphorus concentrations in the reservoir (95% C.I.) in these two periods are as follows:

1971-1972 (89 values)......0.021 ± 0.002 mg P/l
1973-1976 (202 values)......0.012 ± 0.012

About 90% of all values obtained in 1973-1976 were at or below the detection limit (0.01 mg P/l) of the analytical method used for the determination of total phosphorus. For computational purposes, values reported as < 0.01 mg P/l were considered as 0.01 mg P/l. Thus, the confidence interval reported above for the pooled 1973-1976 data is artificaially high.

The low concentrations of nitrate + nitrite nitrogen and total phosphorus obtained in the above monitoring studies are consistent with data generated by other investigators (Sheehan, 1983).

NER also performed nutrient analyses of sediments collected with an Ekman dredge from each branch of the reservoir during each quarter of 1973 (NER, 1973). There is no significant difference among means (SNK procedure) of organic carbon, nitrogen or phosphorus (mg/kg dry mud) for the four branches. Values obtained from each branch were therefore pooled to obtain the following 95% confidence intervals:

Organic Carbon......130,927 ± 61,320 mg C/kg

Total Nitrogen........6,912 ± 3,186 mg N/kg

Total Phosphorus........382 ± 240 mg P/kg

The ratio of the mean values of organic carbon, total nitrogen and total phosphorus is 343:18:1.

Metals

Reed (1947) reports that within the first few years of filling the reservoir (1940-1942), the maximum annual concentrations of iron in surface waters were typically $\geq$ 0.3 mg Fe/l and, in bottom waters, $\geq$ 1.8 mg Fe/l. Mean annual values in this period ranged from 0.15 mg Fe/l to 0.25 mg Fe/l in surface waters, and from 0.45 mg Fe/l to 1.5 mg Fe/l in bottom waters. From 1943 through 1946, mean annual concentrations of iron in surface waters were < 0.18 mg Fe/l and, in bottom waters, < 0.6 mg Fe/l. Reed also reports that manganese was virtually absent (i.e., < 0.01 mg Mn/l) in surface water throughout the seven year period.

Annual concentrations of iron in surface waters in each branch in the period 1971-1976 (NER, 1972-1977) were partitioned into two groups: those generated in the summer during thermal stratification (July-September), and those generated when the water column was not thermally stratified. Only data generated during non-stratified periods were analyzed for significant differences among means. This approach reduces the bias of low concentrations in surface waters which may be due to the precipitation of ferric hydroxide from the well oxygenated epilimnion.

There are significant differences among means (SNK procedure) for the four branches in 1971, 1973, 1974 and 1975. In 1971, 1973 and 1974, means for the eastern and northern branches are not significantly different, but the means of both are significantly greater than the means for the main

and western branches. Data obtained from the eastern and northern branches and from the main and western branches were therefore pooled for each year. Values (95% C.I.) for the pooled eastern and northern branches are as follows:

1971 (19 values)......0.19 ± 0.09 mg Fe/l
1972 (9 values)......0.01 ± 0
1973 (16 values)......0.14 ± 0.03
1974 (18 values)......0.13 ± 0.04
1975 (18 values)......0.11 ± 0.07
1976 (17 values)......0.07 ± 0.04

There are significant differences ($p < .05$) among these means, but no significant linear regression against year ($r^2 = 0.03$). There are no significant differences among the yearly means for the pooled main and western branches. The six-year confidence interval (95%) for these pooled values is 0.05 ± 0.02 mg Fe/l.

Annual concentrations of manganese in surface waters in each branch in the period 1971-1976 (NER, 1972-1977) were partitioned and analyzed in the same way as were concentrations of iron.

There are no significant differences among the means for the four branches during periods of non-stratification in each year. The values for the four branches were therefore pooled for each year. These values (95% C.I.) are as follows:

1971 (34 values)......0.043 ± 0.008 mg Mn/l
1972 (17 values)......0.014 ± 0.004
1973 (24 values)......0.023 ± 0.015
1974 (36 values)......0.024 ± 0.011
1975 (35 values)......0.032 ± 0.018
1976 (34 values)......0.010 ± 0

There are significant differences among these means ($p < .05$) but no significant linear regression against year ($r^2 = 0.04$).

Analyses of iron and manganese concentrations in sediments collected from each branch of the reservoir during each quarter of 1973 (NER, 1973) show no significant differences among means for the four branches. Values obtained from each branch were therefore pooled to obtain the following 95% confidence intervals:

Iron (15 values)......13,269 ± 4,117 mg Fe/kg
Manganese (15 values)...... 1,508 ± 1,613 mg Mn/kg

There are significant ($p < .05$) differences between annual mean concentrations of sodium (SNK procedure) in surface waters in the eastern and northern branches and the main and western branches in 1971, but not in any year in the period 1972-1976. Values for the eastern and northern branches and for the main and western branches were therefore pooled for each year in the period 1971-1976 (NER, 1972-1976). Yearly concentrations in the eastern and northern branches (95% C.I. of pooled values) are as follows:

1971 (26 values)......3.73 ± 0.34 mg Na/l
1972 (18 values)......3.90 ± 0.44
1973 (12 values)......3.66 ± 0.41
1974 (24 values)......2.66 ± 0.25
1975 (25 values)......3.36 ± 0.44
1976 (25 values)......2.50 ± 0.10

There are significant differences among these means (SNK procedure) and a significant linear regression (ANOVA) against year ($r^2 = 0.22$; slope = -0.20). There is also substantial variance unexplained by the regression.

There are no significant differences among the yearly means of the pooled main and western branches. The six-year confidence interval for the pooled main and western branches (128 values) is 2.92 ± 0.14 mg Na/l.

There are no significant differences among annual mean concentrations of zinc (SNK procedure) in surface waters in the four branches in any year in the period 1971-1976 (NER, 1972-1977). Values obtained in the four branches were therefore pooled for each year. There are no significant differences among the annual means of the pooled data in the period 1972-1976; data obtained in these years were therefore combined for comparison with data obtained in 1971. The 95% confidence intervals are as follows:

1971 (56 values)......0.040 ± 0.010 mg Zn/l
1972-1976 (197 values)......0.013 ± 0.001

There is a significant difference ($p < .05$) between these means.

In 1971-1976, some relatively high concentrations of mercury (i.e., > 2.0 μg Hg/l) were observed in the surface waters in each branch of the reservoir (NER, 1972-1976). These values (μg Hg/l) are as follows:

	Eastern Branch	Northern Branch	Main Branch	Western Branch
1971	8.0	23.3	2.7	39.0
1974	200.0	300.0	300.0	100.0
1975	4.1	---	---	3.9
1976	84.3	3.0	16.0	11.4

These excessively high values were most often observed in late spring (May-June); some were observed in early autumn (August-September).

More recent data on concentrations of metals in surface waters were generated through the analysis of quarterly composited, monthly samples

(December 1977-February 1980) or of single quarterly samples (November 1980-August 1981) collected in the immediate vicinity of Shaft 12 (NER, 1978-1981). Metals included arsenic, barium, cadmium, chromium, iron, lead, manganese, mercury, selenium, silver, sodium and zinc. All values were within maximum contaminant levels (MCLs) of Federal and State regulations (MDEQE, 1977 et seq.; EPA, 1979). Reported concentrations of iron, manganese and zinc were consistent with values obtained in the period 1971-1976. All reported concentrations of mercury in 1977-1981 were < 2.0 μg Hg/l.

Other Parameters

Other key parameters which are of particular importance for the minimum pool determination include dissolved oxygen, organic chemicals (including pesticides), and radioactivity.

Reed (1947) reports that dissolved oxygen was depleted in the bottom waters (30-60 ft.) north of Winsor Dam in August of 1940 (the first year after filling the reservoir). From 1940 through 1942, the minimum concentration of dissolved oxygen in bottom waters ranged from 0% to 45% saturation. From 1943 through 1946, the minimum concentration in bottom waters ranged from about 29% to 45% saturation. Throughout the period 1943-1946, the annual average concentration of dissolved oxygen in surface waters ranged from about 86% to 98% saturation; the annual average concentration in bottom waters ranged from about 80% to 85% saturation.

In the period June-August 1967, Reynolds and Erickson (Unpublished Data; Erickson and Reynolds, 1969) obtained depth profiles for dissolved

oxygen and temperature at a number of locations in the eastern, northern and main branches of the reservoir. Values for dissolved oxygen were obtained at each 1-meter depth of the water column and were recorded as percent saturation. Ranges and means of these values are included in Table 5.

As indicated in Table 5, the mean concentration of dissolved oxygen in the eastern and northern branches fell to about 50% saturation at a depth of about 10-13 meters. The lowest mean concentration of dissolved oxygen in the main branch was slightly above 50% at a depth of about 20 meters. A summary of these data with respect to water stratum is included in Table 6. In this summary, the metalimnion is defined as that stratum in which there is at least a 1°C difference in temperature per meter (Odum, 1971; Smith, 1980; Wetzel, 1975).

The dynamic changes in metalimnetic and hypolimnetic waters in each branch from June through August are most probably related to the process of thermal stratification. For example, Erickson and Reynolds (1969) reported that the timing and magnitude of thermal stratification were different in the three branches of the reservoir during the summer of 1967. Maximum stratification in the eastern and northern branches (as measured by relative thermal impedence) occurred in late July- early August, but the eastern branch stratified more strongly than the northern branch. The main branch stratified in about mid-August, and was comparable in strength to the maximum stratification observed in the northern branch. The concentration of dissolved oxygen in the hypolimnion of the eastern branch (August 16, 1967) ranged from about 5% to 15% saturation; at a hypolim-

Table 5

Dissolved Oxygen (% Saturation), June-August 1967*

	Eastern Branch			Northern Branch			Main Branch		
Depth Meters	No. of Values[1]	Range	Mean[2]	No. of Values	Range	Mean	No. of Values	Range	Mean
0	10	95-105	99	4	97-99	98	10	97-107	100
1	10	87-106	98	4	95-100	98	10	97-107	101
2	10	87-106	97	4	94-101	97	10	98-108	101
3	10	88-103	96	4	93-102	97	10	97-108	100
4	10	88-102	95	4	90-102	96	10	98-108	101
5	10	82-96	91	4	89-98	95	10	96-108	100
6	10	69-94	86	4	86-97	94	10	96-109	100
7	10	54-92	81	4	71-96	89	10	95-108	100
8	10	32-89	65	4	60-95	83	10	95-112	101
9	10	23-88	62	4	47-90	66	10	86-110	99
10	10	15-87	60	4	43-87	55	9	64-104	89
11	8	11-83	52	4	32-76	45	8	48-94	74
12	8	8-82	51	4	14-74	39	6	44-88	64
13	7	6-82	48	2	24-25	25	6	33-86	60
14	5	6-79	49	1		21	4	44-81	66
15	5	5-78	48	0			4	43-79	65
16	5	4-75	47				3	64-76	68
17	3	12-59	34				3	62-63	63
18	0						3	59-70	63
19							3	56-66	60
20							3	55-63	57
21							3	44-61	53

*Reynolds and Erickson, Unpublished Data.

[1]All values for range and mean are dissolved oxygen % saturation.

[2]Rounded off to nearest integer.

Table 6

Variation of Dissolved Oxygen with Depth in Major Branches of Quabbin Reservoir*

Branch of Reservoir	Water Stratum	No. of Values[1]	Range of Depth (m) of Stratum	Dissolved Oxygen (% Saturation) 95% C.I.
	Epilimnion	58	0-7	95.9 ± 1.3
Eastern	Metalimnion	30	2-10	66.1 ± 9.5
	Hypolimnion	63	5-17	59.0 ± 7.3
	Epilimnion	30	0-8	95.8 ± 1.5
Northern	Metalimnion	17	5-12	57.1 ± 13.3
	Hypolimnion	8	9-14	53.5 ± 25.6
	Epilimnion	95	0-10	99.5 ± .8
Main	Metalimnion	33	7-15	79.2 ± 8.4
	Hypolimnion	27	13-21	63.0 ± 4.4

*Reynolds and Erickson, Unpublished Data.

[1]All values obtained in period June-August 1967.

netic temperature of 12°C, this is equivalent to about 0.5-1.6 mg O/l. The concentration of dissolved oxygen in the hypolimnion of the main branch (August 29, 1967) ranged from about 55% to 70% saturation; at a hypolimnetic temperature of 13°C, this is equivalent to about 5.6-7.8 mg O/l.

In the period 1972-1976, NER conducted diel studies (samples collected every 2 hours) in the northern branch of the reservoir during July. The minimum concentration of dissolved oxygen at bottom depths (15-20 meters) was 5.1 mg O/l. Mean diel concentrations at the surface in this period ranged from 84% to 106% saturation and are comparable to concentrations observed by Reynolds and Erickson in the surface water in the northern branch in 1967. Mean diel values at bottom depths in this period ranged from 53% to 64% saturation. These values are a little more than twice the values observed by Reynolds and Erickson in the bottom waters of the northern branch in 1967.

In 1971, NER monitored the surface waters of the reservoir for 15 organic chemicals and radioactivity (NER, 1972). Organic chemicals incuded aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, heptachlor epoxide, lindane, methoxychlor, organic phosphate and carbamates, toxaphene, 2,4-D, 2,4,5-T, 2,4,5-TP, and phenols. Radioactivity included gross beta activity and gross alpha activity. Only trace amounts of aldrin and lindane (< 0.0001 mg/l) were detected in a few samples. There was no detectable gross alpha activity, and all detected gross beta activity was < 10 pCi/l.

NER performed additional analyses of organic chemical and radioactivity in 1978, 1979, and 1981 (NER, 1979, 1980, 1981). Organic chemicals included endrin, lindane, methoxychlor, toxaphene, 2,4-D, 2,4,5-TP, gross alpha activity, and gross beta activity. No organic chemicals or gross alpha activity were detected. Gross beta activity ranged from 1 pCi/l to 3 pCi/l.

Physical Data Base

The physical data base includes data on thermal stratification, transit time, residence time, volume and temperature of hypolimnion, temperature of epilimnion, surface area, wind dynamics and light penetration of the water column.

Thermal Stratification

Reed (1947) reports four seasonal periods for the thermal regime of the reservoir in the period 1941-1946:

(1) winter, when there is only slight variation in temperature with depth; surface waters are typically about 1°C, and bottom temperatures are about 2°C,

(2) late spring, when stratification is in its early stage; surface temperatures are about 16°C and bottom temperatures are about 8°C,

(3) late summer, when stratification is well advanced; surface temperatures are about 22°C and bottom temperatures are about 11°C; thermocline is located between 9 and 15 meters below surface,

and

(4) late fall, at the time of overturn, when the reservoir is in complete vertical circulation; the water column is essentially isothermal at about 11°C.

In 1967, Reynolds and Erickson (Reynolds and Erickson, Unpublished Data; Erickson and Reynolds, 1969) measured temperature at 1-meter intervals at six locations in the eastern, northern and main branches of the reservoir. During this period, the depth of the eastern, northern and main branches in the locations monitored was about 16, 13 and 22 meters, respectively. These data were used by J.E. Edinger Associates, Inc. (EAI) to calibrate a computerized hydrodynamic model of Quabbin Reservoir (EAI, 1982a; 1982b; 1982c). The computerized model (see Appendix 1) was developed to simulate a severe drawdown of the reservoir and, thereby, to predict changes in hydrothermal conditions and in hydrodynamics associated with drawdown during the summer period. For purposes of these simulations, the summer period was defined as the period June 21-September 23. Each computer simulation included the effects of wind. The initial simulation was run at reservoir elevation 501 ft., which corresponds to the hydrological conditions of 1967. Simulations at lower elevations (i.e., 490 and 470 ft.) assume the hydrologic conditions of 1967. Finally, the main and eastern branches used in these computerized studies include portions of the northern branch as studied by Reynolds and Erickson in 1967. Key events related to thermal stratification as modeled in these computerized simulations are included in Table 7.

Table 7

Summary of Key Events Related to Thermal Stratification;

Results of Computer Simulation*

Reservoir Stage (ft.)	Reservoir Branch	Events Related to Thermal Stratification[1]: Date of Onset of Stratification	No. Transient Overturn Incidents[2]	Date of Onset of Seasonal Overturn
	Eastern	April 30	5	October 12
501[3]	Main	April 30	5	Later than October 12
	Western	April 30	6	Later than October 12
	Eastern	April 30	5	September 27
490	Main	April 30	5	Later than September 30
	Western	April 30	5	Later than September 30
	Eastern	May 27	6	August 25
471	Main	April 30	8	Later than September 30
	Western	April 30	7	Later than September 30

*EAI, 1982c.

[1]Summer period considered is June 21-September 23.

[2]Transient overturn incident is defined as mixing to a depth of at least 6 meters in the summer period.

[3]Elevation 501 ft. corresponds to elevation of reservoir in summer of 1967; elevation is relative to sea level at Boston.

Transit Time

The hydrodynamic model of the reservoir developed by EAI is capable of determining transit times of different water masses and includes wind as a key factor influencing reservoir hydrodynamics. However, to date, budgetary constraints have prevented the use of this model to determine transit times under different reservoir elevations. One simulation was performed to determine the transit and dilution of hypothetical diversions of Connecticut and Millers River waters into the northern branch of the reservoir (EAI, 1983). This simulation was run at elevation 501 ft. under hydrological and hydrothermal conditions prevalent in the summer in 1967. Results of this simulation may be summarized as follows:

(1) Arrival of waters diverted into northern branch at Shaft 12 in 52-62 days after start of diversion,

(2) Minimal dilution of diverted waters by ambient reservoir waters (i.e., dilution of diverted waters at first steady state concentration of diverted waters at Shaft 12) is 89% in 79 days after start of diversion.

Residence Time

The EAI model (EAI, 1982b; 1982c) was used to determine the following residence times of water masses in each branch of the reservoir under different reservoir elevations. The following determinations are based on average summer flows and the prevailing hydrologic hydrothermal conditions in 1967; all values are days, and were computed by dividing volumes in each branch by mean summer flows associated with each branch:

Reservoir Stage (ft.)	Eastern Branch	Main Branch	Western Branch
501	2,166	6,632	7,871
490	1,351	4,675	6,218
471	544	1,852	4,036

D. Volume and Temperature of Hypolimnion

The volume (billions of gallons) and temperatures (°C) of hypolimnetic waters, as determined by the EAI hydrodynamic model (EAI, 1982b; 1982c) may be summarized as follows:

Reservoir Stage (ft.)	Eastern Branch		Main Branch		Western Branch	
	Volume	Temp.	Volume	Temp.	Volume	Temp.
501	5.08	13.9	53.95	13.0	44.54	11.3
490	1.72	13.6	32.41	13.4	28.78	11.3
471	0.48	16.8	9.69	14.3	12.93	12.3

On the basis of temperature data provided by EAI (EAI, 1982a), NER calculated the range of monthly volumes of hypolimnetic waters (billions of gallons) which are ≤ 18°C in each branch of the reservoir during the period June-September under different reservoir elevations. These determinations are as follows:

Reservoir Stage (ft.)	Eastern Branch	Main Branch	Western Branch
530 (full pool)	13-41	89-165	65-100
501	5-19	50-122	41-75
490	3-10	32-86	30-64
471	< 1-3	10-43	14-39

Temperature of Epilimnion

Summer temperatures of the epilimnion of the major branches of the reservoir under different reservoir elevations were determined by the EAI hydrodynamic model (EAI, 1982b; 1982c). Mean temperatures (°C) in the eastern branch under elevations of 501, 490 and 471 ft. were 19.8, 19.5 and 21.1, respectively; in the main branch, 19.8, 19.7 and 19.7, respectively; and in the western branch, 19.7, 19.5 and 19.6, respectively.

Surface Area

Surface areas of each branch of the reservoir under different reservoir elevations were determined from the stage-surface area curve obtained from the MDC. Surface areas (sq. mi.) are as follows:

Reservoir Stage (ft.)	Eastern Branch	Main Branch	Western Branch
530 (full pool)	9	19	8
501	5	14	7
490	3	12	6
471	1	8	5

Wind Dynamics

Wind shear is a key time-varying boundary condition included in the computerized hydrodynamic model developed by EAI (EAI, 1972b; 1972c). Wind speed and direction data utilized in this model were obtained from the National Oceanic and Atmospheric Administration for Westover Air Force Base, approximately 27 km southwest of the reservoir. Appropriate data for the immediate vicinity of Quabbin Reservoir were not available.

According to EAI, the most important factor in obtaining good agreement between computed and observed temperature profiles in Quabbin Reservoir is the selection of wind shading coefficients for each of the reservoir's branches. Because of differences in morphometry and topography in each branch, different wind shading coefficients were selected for each branch. On the basis of these coefficients, EAI estimated that the minimum wind speed required to cause overturn (i.e., mixing to a depth of at least 6 meters) in any of the three branches was 11.5 mi/hr. This minimum wind speed requirement was constant for reservoir stages of 501, 490 and 471 ft. elevation.

Light Penetration

In the period 1973-1976, NER (1974-1977) recorded Secchi depths in the major branches of the reservoir. The frequencies and timing of these measurements varied greatly from year to year. Also, it was impossible to standardize the light conditions under which the measurements were performed. The overall range of these values was 3-10 meters.

CHAPTER 6

CASE STUDY: DISCUSSION OF DATA BASE AND DETERMINATION OF THE MINIMUM POOL LEVEL FOR QUABBIN RESERVOIR

Introduction

Quabbin Reservoir has experienced major changes in elevation during two periods: 1940-1946 and 1960-1976. The following sections focus on (1) any possible associations between these major hydrologic periods and the available water quality data, and (2) a determination of the minimum pool level in accordance with criteria and considerations previously discussed.

On the basis of the hydrologic data and the experience in operating Quabbin Reservoir, a major drawdown (e.g., > 30 ft.) is unlikely during a short time frame (6-15 months). Experience in the late 1960's and early 1970's indicates a drawdown and subsequent refilling over a period of 10-12 years. Should drawdown again occur to any significant degree (e.g., below 500 ft. elevation), it is likely that the drawdown and any subsequent increase in elevation will extend over several years. Based on hydrologic data for the Quabbin watershed, there is a high probability that one or more major storms will occur in the Quabbin watershed during the period of low pool. High stream flows combined with low pool conditions can be expected to have an important influence on water quality in large areas of the reservoir due to the reduced dilution potential of the ambient reservoir. The most important dilutional effects would most likely occur in the eastern and northern branches of the reservoir, due to

their smaller storage potentials. While the extent of the change in water quality in a lacustrine system cannot be predicted on the basis of dilutional effects on inflow waters alone, it is reasonable to assume that the probability and the magnitude of the degradation in water quality would increase as the elevation of the reservoir is decreased. However, the testing of this hypothesis by means of an existing data base is highly limited by the small number of historic low pools.

Discussion of Data Base

Phytoplankton

The available data indicate that the density of phytoplankton in the summer has remained essentially constant from the period of initial filling of the reservoir through the period of severe drought. Summer phytoplanktonic densities vary from place to place in the reservoir but are consistently indicative of oligotrophic waters. Changes in the composition of the phytoplankton have been noted. During the period of initial filling and through the summer of 1948, diatom species predominated in mid-summer; cyanophycean populations tended to increase in late summer and early autumn. During the latter years of drought and subsequent recovery of the reservoir, chlorococcoid species appeared to become dominant. However, in the mid-1970's, chlorococcoid species appeared to diminish.

There is no clear evidence that the observed changes in phytoplanktonic communities are associated with changing levels of the reservoir. Diatom species are typically characteristic of newly impounded reservoirs, as are periodic blooms of blue-green algae (Baxter, 1977). As impound-

ments age, a variety of factors can influence subsequent development of the phytoplankton, including bacterial-algal interactions (Cole, 1982; Delucca and McCracken, 1976; Hobbie and Wright, 1965), and nutrient limitation (Tilman et al., 1982; Kalff and Knoechel, 1978). More recently, there has been increasing evidence that atmospheric deposition of acids influences the composition of the phytoplanktonic community (Haines, 1981; Linthurst et al., 1983). These factors are not necessarily influenced by reservoir drawdown.

Total Coliform Bacteria

The densities of total coliform bacteria in Quabbin Reservoir vary from place to place in the reservoir. Generally, smaller densities are observed in the main and western branches and larger densities, in the eastern and northern branches. This may reflect the natural treatment capacity of the reservoir which is heavily infleunced by relatively long hydrologic retention and transit periods. All observed densities during the period of severe drought and in subsequent years in which the reservoir was at or near full pool are within the range typically associated with surface runoff from protected watersheds (Kuznetsov, 1970). No relationship between reservoir stage and summer bacterial density was observed in the period 1966-1968 and 1971-1979, during which reservoir capacity fell from full to low pool (1967) and then rose again to full pool (late 1970's).

Fish

The establishment of a cold-water fisheries in Quabbin Reservoir has been largely the result of several fish management programs conducted in various periods from 1952 through 1970. Warm-water fisheries have been an important resource since 1946. There is general agreement among investigators that reservoir drawdown during the period of severe drought had adverse effects on both cold- and warm-water species. These adverse impacts are associated with the reduction of spawning of forage fish for cold-water species and the elimination of spawning habitat of largemouth bass.

The duration and scheduling of reservoir drawdown have been shown to be important factors influencing the effects of lake drawdown on fish (McAfee, 1980). Lake drawdown has two direct quantitative effects on fish habitat. One effect is a reduction in the area of habitat, and the other is a reduction in the volume of habitat. There is dramatic reduction in surface area and hence in subsurface habitat as Quabbin Reservoir decreases in water level. There are also significant reductions in the volume of habitat as the reservoir undergoes progressive drawdown. However, the severe diminution in forage fish densities in the mid-1960's may not have resulted solely from the lowering of reservoir level. In the same period of time, the MDC initiated a program for the chemical poisoning of these forage fish which had become an operational nuisance. The relative contribution of this program and the lowering of reservoir level to the diminution of forage fish densities cannot be determined.

Littoral Vegetation

There is no evidence that the growth of vegetation in exposed littoral areas during the period of severe drought had any measurable impact on water quality in the reservoir in subsequent years as the reservoir refilled and inundated that vegetation. This may be because Quabbin Reservoir is oligotrophic and can absorb a major drawdown and recovery cycle without measurable impacts on water quality. Also, the large volume of the reservoir, even at lowest pool level in 1967 (i.e., about 225 billion gallons), results in an extremely high dilution of nutrients released from inundated vegetation.

Studies in other watersheds have indicated that nutrients released from herbaceous plants are typically relased at greater rates, contain a greater quantity of nutrients per unit weight of vegetation, and are generally more available per unit area than nutrients released from woody plants (Balla et al., 1975). It is therefore possible that future drawdown events which may be shorter in duration (and therefore preclude succession of shoreline vegetation to woody species) and higher in frequency may result in greater inputs of nutrients from herbaceous vegetation into the reservoir than are estimated to have occurred through the inundation of largely woody species in the early 1970's.

Turbidity

Turbidity values during the period of initial reservoir filling were typically high, but declined steadily after the first few years of reservoir operations. Available data during the period of drawdown in the

1960's and subsequent refilling in the 1970's do not indicate any relationship between low elevation and turbidity.

Generally, the waters in the main and western branches of the reservoir have lower turbidity values than the waters in the northern and eastern branches. Thus it appears that the longer the water mass remains in the reservoir, the greater the tendency for "fallout" of suspended materials from the water column. This fallout is one of the recognized mechanisms of the natural treatment capacity of waters and results in reduced turbidity values (Welch, 1952; Symons, 1969).

Color

Color in Quabbin Reservoir appears to have followed a similar pattern as turbidity since the period of initial filling. There does not appear to be any relationship between reservoir level and color in the western and main branches. There is some evidence of a general decline in color in the eastern and northern branches over the summer periods in 1971-1976. The reason for such a trend is unknown, but it may also be indicative of the water treatment capacity of the reservoir returning to full pool. As with turbidity, a longer residence time and/or higher dilution potential of the reservoir appears to reduce the color of the water column. Again, this is one of the well known effects of the natural treatment process in lakes and reservoirs (Welch, 1952; Hutchinson, 1957).

Nutrients

Concentrations of nitrogen and phosphorus in each branch of the reservoir have remained extremely low in the period 1971-1976. Data from earlier years were not available for review. However, in light of the relatively low densities of phytoplankton observed since the 1940's, nutrient concentrations in surface waters in the summer have probably remained consistently low since the formation of the reservoir. Generally, the concentrations of nutrients in bottom waters are higher than concentrations in surface waters (NER, 1972-1977). These findings are consistent with the findings of numerous studies which have focused on the role of bottom sediments as important sources of nutrients for overlying waters (Thibodeaux and Cheng, 1976; Guthrie _et al._, 1975; Elder _et al._, 1979). Diel shifts in thermocline depth (Hirshburg _et al._, 1976) have been shown to result in the vertical transport of nutrients long before complete lake mixing occurred, and that this transport mechanism can support summer/fall algal blooms (Elder _et al._, 1979). While some diel data on nutrients are available for selected portions of Quabbin Reservoir, these data were not collected prior to, during and after reservoir drawdown in the mid-1960's. Thus, it is unknown if historic drawdowns of the reservoir in the 1960's resulted in short-term or transient enhancements of nutrient concentrations in the epilimnion.

Metals

The concentrations of iron and manganese have remained consistently low since the first few years after the initial filling of the reservoir.

There is no evidence of any relationship between reservoir drawdown during the period of severe drought and concentrations of iron or manganese. The concentrations of sodium and zinc typically remained low throughout the period 1971-1976. There is some indication that concentrations of sodium of zinc may actually have declined in this period. Some high concentrations of mercury were observed in the period 1971-1976; however, only trace concentrations were observed in the period 1977-1981. Only trace concentrations of other metals included in the Massachusetts Drinking Water Regulations were observed in the period 1977-1981. It is clear from these observations that metals in the surface water of the reservoir (with the possible exception of mercury) do not present any clear threat to public health. However, there is the potential for metals sequestered in bottom sediments to become suspended in the water column, either through the resuspension of bottom sediments at overturn of the water column, or through desorption or solubilization due to changes in pH and concentrations of dissolved oxygen which may also accompany overturn of epilimnetic and hypolimnetic waters (Symons, 1969).

Dissolved Oxygen

Dissolved oxygen in the epilimnion of Quabbin Reservoir is typically close to saturation. However, metalimnetic and especially hypolimnetic water masses can vary considerably in dissolved oxygen. There have been at least two periods in which studies have indicated very low oxygen levels (i.e., $<$ 10% saturation). Oxygen levels were very low or even depleted in bottom waters during the period of filling the reservoir, when

surface elevation was still below 500 ft. During the drought of the 1960's, dissolved oxygen in the hypolimnion of the eastern branch was often below 10% saturation. The northern branch also became relatively low in dissolved oxygen, often below 30% saturation. In the years subsequent to the severe drought of the 1960's, concentrations of dissolved oxygen in the hypolimnion in all branches were greater than 50% saturation. Thus it appears that the hypolimnion in the reservoir experienced reduced oxygen levels even during periods of full pool and that these oxygen levels were further reduced during periods of reduced reservoir elevations. Various mechanisms may cause reduced concentrations of dissolved oxygen in hypolimnetic waters during periods of reservoir drawdown, including an increase in hypolimnetic temperature which affects solubility of oxygen and biological respiration; increased respiration in the hypolimnion due to decreased dilution of inflow waters containing detritus; decreased frequency of overturn events due to reduced wind sheer at low elevations; and increased sedimentation of organic materials into bottom waters due to increases in transit and residence times. The relatively small increase in hypolimnetic temperature (e.g., $< 3°C$) resulting from drawdown (see below) seems unlikely to result in a significant decrease in concentrations of dissolved oxygen in the hypolimnion during the summer or in an important increase in biological respiration. Also, the results of drawdown simulations using a hydrodynamic model of the reservoir indicate that the frequency of overturn events during the summer increases with decreasing reservoir elevation. Similar simulations indicate that residence times in the major branches decrease with decreasing elevation. This

finding contradicts the possibility of an increase in sedimentation in the hypolimnion at lower elevations. The possibility remains that reduced dissolved oxygen concentrations in the hypolimnion at low reservoir elevation may be associated with an enhanced concentration of detritus as a result of reduced dilution potential.

Organic Chemicals and Radioactivity

Only trace amounts have been observed in a few locations in the reservoir since 1971. Concentrations show no temporal or spatial pattern, and show no relationship to changes in reservoir stage which occurred in this period.

Thermal Stratification

Quabbin Reservoir undergoes summer stratification in each major branch. The depth of stratification in the main and western branches has remained essentially the same since 1941. During the period of severe drought in the 1960's, the metalimnion in the eastern and northern branches often extended to within several meters of the bottom muds. Thus, there was often a poorly developed hypolimnion in these branches. However, even during the period of severe drought, the main branch stratified strongly, producing a hypolimnion which extended to about 10 meters from the bottom.

Stratification is influenced by a number of factors related to depth of the water column (including solar absorption, molecular diffusion, and convective mixing) as well as by weather and morphometry of lake basin

(Hirshburg et al., 1976; Ford and Stefan, 1980). It is therefore reasonable to assume that reservoir drawdown in the mid-1960's resulted in an overall deeper stratification (and thus a thinner hypolimnion) in the eastern and northern branches than would otherwise have occurred. The hydrodynamic model for the reservoir supports the hypothesis that reservoir drawdown does affect thermal stratification in the reservoir. This model suggests that a lowering of reservoir stage from 501 to 471 ft. elevation can delay initial stratification in the eastern branch by about a month, and cause earlier seasonal overturn (by about 1-2 months) in each branch. Also, the model suggests that the number of transient overturn incidents during the summer months increases with a lowering of reservoir stage from 501 ft. (5-6 incidents) to 471 ft. elevation (6-8 incidents).

Time and budgetary constraints prevented the use of varying tests of "overturn events" in simulations using the hydrodynamic model. The single test for an overturn event was homothermal conditions in the water column. However, it is also possible for mixing to occur within a heterothermal water column, depending upon conditions of wind speed and temperature differences between water strata. Thus, the results of the hydrodynamic simulations of Quabbin Reservoir with respect to overturn incidents should be viewed as conservative. It should also be noted that all hydrodynamic simulations were based on calibration of the model to hydrodynamic conditions in the summer of 1967. These conditions include reservoir withdrawal rates that are not necessarily the same from year to year. Ideally, simulations should consider a range of withdrawal rates in order to project more realistically the potential hydrodynamic effects of reservoir

drawdown.

Transit and Residence Times

Specific data on transit times in Quabbin Reservoir are not available for consideration in this analysis. The results of the hydrodynamic modeling of the reservoir do indicate that lowering the reservoir stage results in large reductions in residence times in each branch of the reservoir. The reduction is particularly large in the eastern and main branches of the reservoir. It may therefore be concluded that reductions in elevation may be expected to reduce the transit times for the movements of water masses from one region of the reservoir to another region. Again, it should be noted that projections of residence times under lowered pool conditions are based on the hydrodynamic conditions of 1967 and are thus directly influenced by withdrawal rates which were characteristic of the 1967 summer period.

Volume and Temperature of Hypolimnion

The hydrodynamic model of Quabbin Reservoir demonstrates that reservoir drawdown results in an increased temperature of the summer hypolimnion. The projected increase in temperature is small (about 1-3°C) when the reservoir is drawn down from 501 to 471 ft. elevation. The model also demonstrates that drawdown results in significant reductions in the volume of the hypolimnion in each branch of the reservoir. The greatest impact is in the eastern branch, and the smallest impact is in the western branch. The degree of impact depends upon the initial and final stages of

the drawdown. For example, a stage reduction from 530 to 501 ft. elevation results in about a 55% reduction in the volume of the hypolimnion in the eastern branch. A further reduction to 471 ft. elevation virtually eliminates the hypolimnion in the eastern branch. The volume of the hypolimnion in the other branches is also significantly reduced by reservoir drawdown.

Temperature of Epilimnion

The hydrodynamic model for Quabbin Reservoir indicates that reservoir drawdown has a relatively small effect on the average summer temperature of the epilimnion. For example, the eastern branch would experience about a 3°C increase in temperature with a drawdown from 501 to 471 ft. elevation; the western arm would experience about a 1°C increase with the same drawdown.

Surface Area

Reductions in reservoir stage from full pool elevation results in significant reductions in surface area of the reservoir. However, the reductions in surface area are not uniform throughout the reservoir. For example, a reduction in stage to 501 ft. elevation results in a 45% reduction in surface area in the eastern branch, a 25% reduction in the main branch, and about a 13% reduction in the western branch. There are several implications of the reduction in surface area. For example, reduced surface area also results in reductions in aquatic habitat. It also results in increases in exposed areas which subsequently revert to terres-

trial vegetation. Finally, reduction in surface area results in reduction in the area of the water column in which natural purification or degradation processes occur. These processes include photodecomposition and bleaching of color in the water.

Wind Dynamics

The hydrodynamic modeling of Quabbin Reservoir indicates that wind speeds of 11.5 miles per hour or greater can cause overturn of the summertime water column down to at least 6 meters in depth. As drawdown occurs, the probability of these wind-driven overturn events extending down to the bottom of the reservoir increases. Thus the probability of stirring up bottom sediments into the water column also increases with decreasing elevation of the reservoir. The following information on average depths (meters) in the reservoir as a function of elevation illustrates these points:

Reservoir Stage (ft.)	Eastern Branch	Main Branch	Western Branch
530	10.9	17.3	23.1
501	7.0	12.3	16.5
490	5.9	10.7	14.4
471	4.6	8.5	11.7

As indicated by these data, the eastern branch of the reservoir at elevation below 490 ft. would be subject to overturn events which could stir up the bottom sediments in a substantial portion of that branch (approximately 50%).

Light Penetration

Field observations in Quabbin Reservoir indicate that light penetration as measured by Secchi disc depths is generally in the range of 3-10 meters. As drawdown occurs, there is increasing probability that light will penetrate to benthic habitats in the reservoir. For example, as the reservoir elevation decreases below 490 ft. elevation, the depth of substantial portions of the northern, eastern and main branches declines to less than 10 m in depth. These areas would be within the Secchi depths measured in the reservoir. Since light useful in photosynthesis actually penetrates deeper than the Secchi depth (Kuznetsov, 1970), much of the bottom of the reservoir would receive sufficient sunlight to support benthic vegetation. This assumes, of course, that the color and turbidity of the water column do not substantially increase over values typically observed in the 1960's and 1970's.

Determination of the Minimum Pool Level

Determination of a minimum pool level requires consideration of appropriate drinking water regulations as well as regulations pertaining to other uses of reservoir waters, including recreation and wildlife management. Also, reservoir drawdown may influence water quality differently at specific locations within the reservoir. For purposes of this discussion, the focus is on the Massachusetts Water Quality Regulations (MDEQE, 1977 et seq.), which include standards for drinking water and for recreation and wildlife management. Potential violations of water quality standards in the vicinity of intakes to aqueducts as well as other selected

locations are considered in order to estimate the potential for violations at the mid-point of the main branch of the reservoir. Finally, the following sections include summaries of historical violations of water quality as well as violations which may be predicted on the basis of the existing data base, including data derived from the computerized hydrodynamic model of the reservoir.

Violations of Drinking Water Standards

The major historic violations of drinking water standards in the vicinity of Shaft 12 were those which occurred within the first few years of filling Quabbin Reservoir. Parameters which did not meet current standards included turbidity, color and iron.

Periodic violations have been subsequently observed with respect to total coliform bacteria and mercury. The violations in densities of total coliform bacteria have been infrequent and minor, and are quite typical of any large body of water receiving runoff from a protected, forested watershed. In the case of mercury, the violations appear sporadic and were limited to a specific time frame (1971-1976). During this period the reservoir was returning to full pool from an elevation of about 500 ft. The reason for these sporadic high values of mercury is unknown, nor is it known if they were related to the drawdown in the 1960's. Based on the other data available from the late 1960's and early 1970's, there were no specific violations of drinking water standards at Shaft 12 which can be attributed to the drawdown.

It is assumed that wind driven overturn incidents during the summer period may result in specific violations of water quality standards. Based on results of the hydrodynamic model of the reservoir, it is unlikely that overturn incidents, which could increase turbidity values and concentrations of other parameters (including metals) in the water column, would occur in the main branch down to elevation 470 ft. At elevations less than about 470 ft., residence times and the dilution potential in the eastern branch and portions of the northern branch would be severely reduced and therefore possibly result in enhanced concentrations of total coliform bacteria, color and turbidity in the main branch in the vicinity of Shaft 12.

The data base for the period 1940-1981 indicates that the violations in current drinking water standards in the vicinity of the Chicopee intake were similar to those discussed above for waters in the vicinity of Shaft 12. Violations of primary and secondary standards occurred during the earlier years. With the exception of the same sporadic violations of the mercury standard as seen at Shaft 12, no other violations have been observed after the reservoir reached full pool.

Future violations attributable directly to drawdown are unlikely for elevations down to 470 ft. The western branch is deep, and major overturn incidents reaching the bottom in summer are even less likely than for the water column near Shaft 12.

Other areas of the reservoir are likely to experience some violations of drinking water standards as the reservoir experiences drawdown. The eastern and northern branches of the reservoir are likely to experience

increases in concentrations of total coliform bacteria, turbidity, color and iron as the reservoir experiences the dynamic changes associated with drawdown. These changes are likely to increase at elevations below 490 ft. This is because thermal conditions, depths, overturn events and storm episodes combine to increase the probability of adding contaminants to the water column. How long such contaminants would remain in the water column cannot be predicted with any precision. Experience in the early 1940's indicates that turbidity and color decreased significantly within a few years. However, this was a period of increasing elevation of the surface of the reservoir. Should turbidity and color reach values above the standards in the northern area, and should these violations occur at low elevations (e.g., 470-490 ft.), the residence time may not be sufficient to improve water quality by the time the water mass reaches the vicinity of Shaft 12. Thus, the risks of violations of drinking water standards at Shaft 12 increase as the reservoir drops below 490 ft. The risks also increase as the period of sustained drawdown becomes longer. Actual and potential violations of drinking water standards under various reservoir elevations are summarized in Table 8.

Violations of Other Standards

During the period of initial filling of the reservoir, the dissolved oxygen levels in deep water were below the current standards for cold-water fisheries. During the period of drawdown in the 1960's, dissolved oxygen in the lower depths (i.e., below the thermocline) of the eastern and northern branches was below standards. During the years following the

Table 8

Summary of Assessment of Violations of Drinking Water Standards

Reservoir Elevation (ft.)	Comments on Violations of Drinking Water Standards
530-500	Periodic violations of standard for mercury were observed; it is unknown if such violations were due to resuspension of bottom sediments or to other causes.
505-495	No violations directly attributable to drawdown were observed near Shaft 12 or the Chicopee Intake in the mid-1960's to 1970's.
Below 490	Violations in turbidity, color and iron were observed during the filling of the reservoir in the early 1940's.
490-470	Violations in turbidity, color and metals likely in the eastern and northern branches of the reservoir (assuming resuspension of bottom sediments during overturn incidents); violations near Shaft 12 and the Chicopee Intake are possible but not likely.
Below 470	Violations in turbidity, color, metals and coliform bacteria due to hydrologic and wind-driven overturn events are likely; frequency and duration of violations increase with lowering of elevations; frequency and duration of violations greatest in northern and eastern ranches.

drought and during which reservoir depth increased substantially, there were no violations of standards which can be attributed directly to the inundation of the extensive littoral vegetation which had developed over several years. However, the effects of additional drawdown, vegetative growth and inundation cycles are unknown.

Drawdown of the reservoir below 490 ft. is likely to result in various violations of water quality standards. Increases in turbidity, color and total suspended solids are likely in the eastern and northern branches and in extensive sections of the northern portion of the main branch of the reservoir. Violations in dissolved oxygen standards are also likely in these sections of the reservoir. Nutrients from bottom sediments will likely be resuspended by overturn incidents, and these can be expected to promote period nuisance growth of algae. Because of penetration of sunlight to the bottom, there will likely be growth of nuisance aquatic macrophytes, especially in the eastern and northern branches and in the northern portions of the main branch. These violations will become more pronounced with greater degrees of drawdown below elevation 490 ft. If the reservoir remains at elevations between 470 and 490 ft. for any extended period (several years), the reservoir is likely to eutrophy. A summary of actual and potential violations of other water quality standards under various reservoir elevations is included in Table 9.

Impacts on Fisheries

The impacts of reservoir drawdown on the cold-water fish species of Quabbin Reservoir will depend upon a number of factors, including the

Table 9

Summary of Assessment of Violations of Water Quality Standards Associated with Recreation and Wildlife

Reservoir Elevation (ft.)	Comments of Violations of Water Quality Standards
530-500	Violations of standards at mid-reservoir (in main branch) are not likely.
525-495	No violations of water quality standards attributable to inundation of littoral vegetation observed in late 1960's and early 1970's; effects of additional drawdown, growth of terrestrial vegetation and subsequent inundation are unknown.
505-495	Concentrations of dissolved oxygen below standard were observed in hypolimnion in eastern and northern branches in the 1960's.
Below 490	Concentrations of dissolved oxygen below standard were observed in hypolimnion in main and western branches in the early 1940's; increases in turbidity, color and total suspended solids are likely in eastern and northern branches and northern portions of the main branch; reductions in dissolved oxygen below standard are likely in eastern and northern branches and northern portions of the main branch; increases in nutrients and algal growth are likely in eastern and northern branches and northern portions of the main branch; growth of nuisance aquatic vegetation are likely throughout the reservoir, especially in the eastern and northern branches.
490-470	Sustained period of drawdown (several years) likely to enhance eutrophication of reservoir.

decrease in cold-water habitat, decrease in spawning areas, effects on forage fish, decreases in dissolved oxygen, and increases in water temperature. These and many other factors are linked in complex ecosystem dynamics and precise predictions are impossible.

Experience in the period of the late 1960's indicates that there was an important adverse impact of reservoir drawdown on the cold-water fishery. There is general agreement that the drawdown associated with drought contributed to the diminution of the cold-water fisheries. Reservoir elevation in this period ranged from 495 to 505 ft.

It is likely that reservoir drawdown to about 500 ft. elevation will have several adverse effects on the cold-water fishery of the reservoir. At this elevation there will likely be important reductions in oxygen in the hypolimnion. There will also be important reductions in the volume of the cold-water habitat. For example, at 500 ft. elevation there is a loss of about 30-40% of the cold-water habitat in the summer months. At 490 ft. elevation, over 50% of the cold-water habitat will be lost. Even the deep western branch will experience major losses in the volume of the colder hypolimnion. At elevations of 490-470 ft., it is unlikely that a healthy and viable cold-water fishery can be sustained in the reservoir. However, relatively small local areas in the deepest portions of the reservoir may be able to support some cold-water populations.

The change in the limnological character of the reservoir with drawdowns below 490 ft. will tend to favor many of the fish species which compete well in warm, shallow, and biologically productive ecosystems. As the relative decrease in cold-water populations occurs, there will be

increases in warm-water populations. A summary of actual and potential impacts of reservoir drawdown on the fisheries of Quabbin Reservoir is included in Table 10.

Summary and Recommendation for Minimum Pool Level

The above findings and projections may be summarized as follows:

(1) Violations of drinking water standards near Shaft 12 and the Chicopee Intake are likely to occur at reservoir elevations below 470 ft.; violations are possible but less likely between 470 and 490 ft.; and, violations are highly unlikely above 500 ft.

(2) Violations of drinking water standards at other locations in the reservoir will occur at elevations below 490 ft.

(3) Violations of other standards at a mid-reservoir location (main branch) are likely to occur below 490 ft., but are not likely above 500 ft.

(4) There will be periodic violations of other standards at other locations at elevations above 490 ft.

(5) There will be progressively adverse effects on cold-water fish habitat at all reservoir elevations below 530 ft.

(6) There will be important adverse effects on the cold-water fishery at reservoir elevations below 500 ft.

(7) Below 490 ft. elevation, Quabbin Reservoir will tend to shift toward a predominantely warm-water fishery; localized populations of cold-water populations may persist in the deepest portions of the reservoir.

Table 10

Summary of Assessment of Impacts of Reservoir Drawdown on Fisheries

Reservoir Elevation (ft.)	Comments on Impacts on Fisheries
Below 530	Progressively adverse effects on the habitat for cold-water species.
505-495	Adverse effects on the cold-water fishery occurred in the late 1960's; some of these effects were attributed to drawdown.
500	About 30-40% loss of cold-water habitat will occur in the summer period.
490	Over 50% loss of cold-water habitat will occur in the summer period.
Below 490	Maintenance of a healthy and viable cold-water fishery in the reservoir is unlikely; changes in the ecology of the reservoir will provide good habitat for warm-water species; the reservoir will progressively shift to a predominately warm-water fishery, with changes in relative population densities among current species.

(8) If the reservoir remains between 470 and 490 ft. elevation for several years or longer, there will be major limnological changes and a shift toward eutrophic conditions.

(9) The changes in water quality and aquatic ecology which are likely to occur with significant drawdown (e.g., below 490 ft.) will become progressively more pronounced as the drawdown persists for long periods of time.

Considering the above findings and projections, it is recommended that the minimum pool level for Quabbin Reservoir be established at 490 ft. elevation. At or above this elevation, there is a reasonable expectation that the hydrodynamic characteristics, dilution potential, and natural treatment capacity of the reservoir will persist in sufficient degree to ensure compliance of output waters (at Shaft 12 and the Chicopee Intake) with appropriate water quality standards and the achievement of objectives of on-going management programs.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The data base for Quabbin Reservoir includes a variety of physical, chemical and biological data which were generated over a period which included significant changes in reservoir depth. Changes in reservoir depth were associated with the initial filling of the reservoir (1940-1946) and a period of drought and subsequent recovery (1960-1976).

The most dramatic changes in water quality in the reservoir occurred during the period of its initial filling, and included increases in hypolimnetic dissolved oxygen and decreases in turbidity, color, and concentrations of iron and manganese. Such changes in water quality are typically observed in new impoundments and cannot be used with any assurance as a basis for predicting the effects of subsequent drawdowns on water quality.

During the period of drawdown in the mid-1960's and subsequent recovery, there appeared to be little if any change in water quality in Quabbin Reservoir. However, during this period it was noted that the shallower northern and eastern branches of the reservoir were generally of a lower water quality than the main and western branches with respect to color, turbidity, total coliform bacteria, and hypolimnetic dissolved oxygen. It was also noted that concentrations of certain water constituents were higher in 1971-1972 than in 1973-1976, including total phosphorus, sodium and zinc. It cannot be determined if the decreasing concentrations of these constituents were directly associated with increasing water levels in this six-year period, or with changes in runoff characteristics.

Because of the constraints imposed by the available data base, the determination of a minimum pool level for Quabbin Reservoir was largely based on computerized hydrodynamic simulations of the reservoir. These simulations focused on the influence of reservoir drawdown on destratification of the reservoir during the summer, light penetration to benthic habitat, transit/residence time in the reservoir, increase in hypolimnetic temperature, and the mechanical stirring of bottom muds. Results of these simulations were evaluated with respect to public health and environmental quality criteria appropriate for a domestic water supply which also serves as a cold-water fishery resource.

The usefulness of computerized hydrodynamic simulations of drawdown in the determination of the minimum pool level for Quabbin Reservoir was limited by financial considerations which dictated the following constraints:

(1) Reservoir hydrodynamics were simulated at only a few reservoir elevations,

(2) Transit times between various locations in the reservoir at various reservoir elevations were not determined,

(3) Simulations of overturn incidents did not include consideration of heterothermal conditions of the water column or varying wind velocities and durations,

(4) Overturn incidents were not simulated to investigate horizontal shear velocities at the mud-water interface; thus, it was not possible to estimate the probability of resuspension of bottom sediments in the water column at overturn, and

(5) All hydrodynamic simulations were conducted using reservoir inflow and withdrawal rates for the summer of 1967; thus, it was not possible to estimate the influence of different inflow and withdrawal rates (which might exist during a future drawdown) on reservoir hydrodynamics.

In light of my experience with Quabbin Reservoir, I conclude that it is unlikely that a water quality data base for a reservoir will ever prove to be sufficient to determine a minimum pool level solely on the basis of historic changes in water quality. A hydrodynamic model of a reservoir, in combination with a historic data base, does provide a basis for making such a determination. It is therefore important to address the constraints of hydrodynamic simulation which have been identified above before applying this method to other surface reservoirs.

APPENDIX

GENERAL DESCRIPTION OF THE COMPUTERIZED HYDRODYNAMIC MODEL OF QUABBIN RESERVOIR

Introduction

Hydrodynamic simulation of Quabbin Reservoir was accomplished with a numerical hydrodynamic model developed by J.E. Edinger Associates, Inc. (EAI). This model has been under development by EAI since 1974. Some development of this model has been funded by the U.S. Corps of Engineers Waterway Experiment Station, Vicksburg, Mississippi. The model has been applied to over twenty reservoirs in the United States.

The model was applied to Quabbin Reservoir under contract between EAI and the Metropolitan District Commission (MDC). All simulations of the hydrodynamics of Quabbin Reservoir were coordinated between EAI and New England Research, Inc. (NER), with Paul A. Erickson acting as Project Director for NER and Edward Buchak acting as Project Director for EAI.

General Description of Model

The following general description of the model and of its application to Quabbin Reservoir is abstracted from a technical report provided by EAI to the MDC (EAI, 1982b). The model is a laterally-averaged reservoir model (FORTRAN CODE = LARM). It incorporates the solution of the momentum, continuity, heat and constituent balances and state equations in two dimensions (vertical and longitudinal) and time. The model was specifically developed for water bodies where temperature-induced buoyancy is

important and where lateral homogeneity can be assumed. LARM generated time-varying velocity, temperature and water quality constituent fields and surface elevations on a longitudinal and vertical grid. Use of LARM requires the completion of four tasks as follows:

(1) bathymetric data reduction, code setup and validation,

(2) time-varying boundary condition data analysis and preparation,

(3) verification using observations, and

(4) simulation for other than observed conditions.

Application to Quabbin Reservoir

Bathymetric Data Reduction

Quabbin Reservoir was divided into three branches. Each branch was subdivided into longitudinal segments; the total number of segments for the reservoir was 32. Segment lengths were 2296.70 m in the western branch, and 1784.30 m in the main and eastern branches. The thickness of vertical layers in each segment was 2.0 m. The width of each segment was determined by enlargements of a contour map of the reservoir. for each segment and layer, area was obtained by a planimeter and then divided by segment length to determine average width. This geometric representation was used to obtain a voluem-area-elevation table which was then compared to published stage-volume curves for the reservoir to adjust the location and dimensions of segments.

Locations and dimensions of aqueduct inlets and outlets, locations of gaged tributary inflows and key geometric features of the reservoir were coded into the geometric representation of the reservoir. Ungaged tribu-

taries were distributed around the periphery of the reservoir in proportion to the top width of each segment.

Validation tests at this stage consisted of steady state simulations to check water and heat budgets and to identify anomalies of velocity fields that might indicate errors in the geometric representation of the reservoir.

Time-Varying Boundary Conditions

Time-varying boundary condition data for simulations included (a) meteorological data to compute surface heat exchange and wind shear, (b) inflow rates and temperatures to compute amounts of water and heat advected into the reservoir, and (c) aqueduct withdrawal rates to compute amounts of water and heat advected out of the reservoir.

Meteorological data for 1967 were obtained from the National Oceanic and Atmospheric Administration for Westover Air Force Base. The data were hourly values of dry bulb and dew point temperatures, wind speed and direction, and sky cover. These data were used to compute summary parameters of coefficients of surface heat exchange and equilibrium temperature. Inflow records were obtained from the MDC monthly flow summaries of daily values. No inflow temperature records were available for 1967. An inflow temperature record was therefore synthesized using monthly temperature records published by the U.S. Geological Survey for 1967.

Verification Using Observations

The purpose of verification at this stage is to establish confidence in simulations for other than observed conditions.

The year 1967 was chosen for vertification because it included the historic low elevation of the reservoir surface. Data used in verification included vertical temperature profiles on 31 days at three locations in the eastern branch, and at two locations in the main branch of the reservoir. These data were obtained from Clark University (Reynolds and Erickson, Unpublished data). Water surface elevations were obtained from the MDC.

Comparison of simulated temperature profiles using LARM with actual profiles obtained in 1967 was used to adjust the boundary conditions in LARM. The most important factor in obtaining good agreement between computed and observed temperature profiles was the selection of wind shading coefficients for each of the reservoir branches. These coefficients were used to reduce the observed wind speed at Westover Air Force Base to an effective wind speed at the surface of the reservoir. Sensitivity tests used to obtain these coefficients included full wind, no wind and intermediate wind simulations.

Wind shading coefficients selected were 0.50, 0.60 and 0.25 for the western, main and eastern branches, respectively. A wind shading coefficient of 0.50 means that only 50% of the observed wind velocity at Westover Air Force Base was considered effective for wind shear at the reservoir. Relative values of these coefficients were considered to be in general agreement with the surrounding topography of each branch and with

informal observations of wind patterns provided by Erickson and other investigators at NER.

Simulation of Drawdown Conditions

Simulations of hydrodynamics were based on a series of questions provided by Erickson (NER) to EAI. These questions focused on (a) the timing of spring stratification and fall overturn, (b) transit times of water masses between various portions of the reservoir, and (3) depth-temperature relationships under various conditions of drawdown.

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